

CONSTRUCTIVE USES
OF ATOMIC ENERGY

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CONTENTS

Preface	vii
I Atomic Energy as a Human Asset, by Arthur H Compton	1
II The World Within the Atom, by L. W. Chubb	26
III Atomic Energy in Industry and the Physical Sci ences by Samuel K. Allison	47
IV Industrial Applications of Radioactivity by M. Blau and J. R. Carlin	58
V Atomic Power for Industry by H. Etherington	73
VI Chemical Process Control with Radioactivity by Alan P. Schreiber	89
VII Radioactive Tracers in Metallurgical Research, by E. S. Kopecki	101
VIII Atomic Engines for Aircraft, by Andrew Kalitinsky	112
IX. Ceramics and Nucleonics by A. L. Johnson	123
X. Radioactive Materials in Soil Fertilizer Research, by F. W. Parker	132
XI The Uses of Tracers in Biology by G. C. Butler	145
XII The Medical Uses of Atomic Energy by C. P. Rhoads	159

XIII. Radioactive Tracer Techniques in Pharmaceutical Research, by John E. Christian	173
XIV Nuclear Physics and Medical Research by G Failla	182
Appendix A Chronological List of Highlights Significant to Atomic Energy	189
Appendix B Glossary of Some Important Scientific Terms Used in Atomic Energy	193
Appendix C Bibliography	225
Index	247

PREFACE

Constructive Uses of Atomic Energy attempts to bring into focus our present knowledge about nuclear energy especially its potentialities for purposes other than war. The need for the wider dissemination of information on the subject is generally recognized but, up to now, no compact source book dealing with the possible uses of atomic energy in nonmilitary fields has been available. The articles included represent the end result of a four year search through a great mass of widely scattered literature in an effort to find material which would dispel the common misconception that atomic energy is beyond the comprehension of the layman. Most technical books designed for the general public are written from the inside looking out, that is from the standpoint of the scientist looking out—and often down on—his reader. This collection has been compiled from the outside looking in—from the point of view of the layman groping cautiously through the maze of facts and fallacies regarding the atom and its energy.

Because it is a compilation of contributions from many branches of science and engineering the book has wide appeal. Industrial executives will be furnished conclusive evidence that the use of atomic energy in industry is a definite, not a far

fetches, possibility. Engineers and trained technicians already familiar with the principles of nuclear physics, will find essential information not heretofore available in one book. Those who fear the lethal effects of stray short wave radiations will be assured that, *with proper safeguards* the atomic field presents no more danger than does any other hazardous occupation.

The necessary limitation to only declassified and published information obviously leaves many gaps. No layman after reading this book will understand atoms and atomic energy in detail. But, in spite of ignorance concerning how his car and his radio function, he does not regard them as complete mysteries. If this book leads to his acceptance of the fact of atomic energy and the possibilities of its use, it will have served a useful purpose.

The three appendixes have been prepared primarily for the nonscientific reader. The Chronological List of Highlights affords a brief idea of the important steps in atomic research. The Glossary defines in easily understood terms the many new words and expressions that nuclear energy has introduced into our language. The Bibliography, which lists some of the more recent publications in the field, is intended primarily to serve as a guide to further reading. Whenever possible, original sources are cited, and the selection of titles is based on the quality and continuing value of the material. A unique feature of the Bibliography is the last section which reclassifies all the titles in terms of the source periodicals.

For permission to include these articles I am indebted to many authors and publishers, private industries and govern-

ment agencies. Specific sources are stated in footnotes on the opening page of each chapter.

This volume would not have been possible without the enthusiastic encouragement and indispensable editorial counsel received from many people, among them Morse Salisbury and E. R. Trapnell of the U. S. Atomic Energy Commission's Division of Public and Technical Information, Dr. Paul C. Aebersold, Chief Isotopes Division, Oak Ridge Operations of the Commission, Colonel James P. Cooney, M.C., Armed Forces Special Weapons Project, Herbert Stephens, *Printers Ink*, Dr. Harold Blumberg, Endo Products Co., and Ruth Hooper Larson of New York.

Special thanks are due the following staff members of the Atomic Energy Commission's Division of Public and Technical Information: Dr. A. F. Thompson, Bernard Fry, and Mary C. Devereaux, and Harry R. Gail and Robert T. Scott of the Westinghouse Electric Corporation.

Finally, I wish to acknowledge my debt to all the contributors from whose painstaking articles the plan of this book grew and in the presentation of whose writings I served merely as reporter. My sincere hope is that this indebtedness will be repaid by such added interest in their work as this volume may stimulate.

New York, N. Y.
May 1, 1949

S. C. R.

CONSTRUCTIVE USES
OF ATOMIC ENERGY

CHAPTER I

ATOMIC ENERGY

AS A HUMAN ASSET¹

BY ARTHUR H. COMPTON²

It is with diffidence that we who have been working on the technical aspects of atomic energy present before a group of experts our amateur thoughts with regard to its human implications. Yet action is needed, and only by boldly presenting our thoughts for discussion can a reasonable basis for such action be reached.

The ability to release atomic energy gives mankind great new powers. These powers can be used for good or ill. The first use of atomic energy was as a bomb whose explosion stopped short

¹ This chapter is based on the Franklin Medal Lecture, read November 16, 1945, in the Symposium on Atomic Energy and its Implications. The material is reprinted by permission from *Proceedings of the American Philosophical Society* Vol. 90, No. 1 January, 1946.

² Dr. Arthur Holly Compton, chancellor of Washington University, St. Louis, and Nobel Prize winner (19 7) in the field of physics, directed the work leading to the world's first chain reacting uranium pile at the University of Chicago.

a tragic war with the probable net saving of some millions of lives. Its terrific military destructiveness has made it necessary for us to consider afresh how we may avoid future wars. The dramatic demonstration of its explosive power has however drawn attention away from the significance of atomic energy to our industry, our habits of life, and our culture. It is in such peacetime consequences that atomic energy will eventually mean most to man.

The atomic age has started as a period of keenest rivalry. The rivalry is between nations and social systems. The prize to be won is prosperity and world leadership. It can include peace and security. If only we agree to place war beyond the power of nations, the race is sure to make life of greater value. Such is the prospect of a world strengthened by unlimited power from atomic fission and forced away from war by the examples of Hiroshima and Nagasaki.

HOW SHALL WE PREVENT ANOTHER WAR?

World government has become inevitable. The choice before us is whether this government will be agreed upon or whether we shall elect to fight a catastrophic third world war to determine who shall be master. Unity by agreement will bring greater life. Unity forced by another war will bring death to many millions and disaster to all mankind.

The primary function of this world government must be to prevent international war. With regard to its economic and cultural life, the world has during the past century been developing into a unit in which the welfare of each person depends intimately upon that of the rest of humanity. We have indeed become "members one of another." Such development

has not, however resulted in political world unity. The great destructiveness of an atomic war even to the victor makes it necessary now for self-preservation to insure peace. In a quarrelsome world the only means of insuring peace is, however for the nations to set up an international police force which monopolizes the power to wage war.

Now for the first time, however it becomes feasible for a central authority to enforce peace throughout the world. Before World War II many parts of the earth were difficult of access by a world police. If not a Maginot Line, at least a strong fighting front could keep out a policing army. During the time required to bring this policing army to the scene the defense of the recalcitrant group could be strengthened.

Today this is changed. Fast airplanes, long-range rockets and atomic bombs have now solved the technical problem of bringing to bear on any area at any time whatever destructive force may be required to quell resistance. A central authority having virtual monopoly of these major means of warfare can now be equipped to enforce international peace.

The fact is that the United States now has in its possession a sufficient monopoly of the weapons needed for such policing that it might be able to act in this capacity of world police. That we do not set ourselves up as the world governors is simply because we do not want the job. We feel that world control is the world's business, not ours. We know that, if we should use armed force to prevent other nations from fighting when our own interests were not directly threatened, we should be considered meddlers and should gain only the fear and hate of other nations. We should prefer to withhold our fighting power unless our own safety is directly threatened, and confine our policing activity to our own reasonable share in keeping

order within nations that are not now able to look after their own interests or that may become dangerous to us if not kept under control.

Nevertheless looking ahead it is clear that no mere strengthening of our own might can keep us safe. Our safety cannot be kept secure by our own military development without international control of the new weapons. Whatever our strength, others also can arm so as to inflict upon us disastrous damage if war should come. What is needed is an agreement which will make our safety much surer than could result from our own armed might and which will at the same time provide for elimination of international wars elsewhere throughout the world. It is such an agreement that we should seek, sincerely with determination and with faith that it can be attained with reasonable promptness. The important step³ that has just been made in this direction by the President of the United States and the Prime Ministers of Great Britain and Canada should be welcomed by the entire world.

I am not much concerned with the precise answer to the question of how long it would require before other nations could be prepared to challenge us with atomic weapons. I know they will not do so for the next five years. After twenty five years unless some mutual agreement prevents their development, such countries as Britain, Russia and France could arm themselves with weapons similar to ours if they should want to spend the necessary effort. The time required would not be greatly affected by whether we hold to our own secrets or not. It is in any case only a small part of the lifetime of our nation.

³ Agreed declaration by the President of the United States of America, the Prime Minister of the United Kingdom, and the Prime Minister of Canada, signed at Washington, D. C. November 15, 1945.

that would elapse before we should be faced with the awful possibility of an atomic war

As has been seen by the heads of our governments, now is the time when international agreements can best be made to prevent such a catastrophe. Other nations have not yet developed a pride in their atomic might which could give them dreams of world mastery. Our own effort has paid for itself many times over by stopping the course of World War II. All nations are now laying plans for the postwar years and it will be much easier to shape these plans now on the basis of world government than to stop the wild development of a renegade nation by imposing emergency military controls after it is set in its course.

It may be worth reviewing just what we mean when we refer to the great destructiveness of war in the age of atoms. If the future demands it, science sees no reason to doubt that atomic weapons can be made that are related to the present atomic bomb much as the block buster is to the blunderbuss. Yet even the present atomic bomb is a highly effective weapon. If one bomb will devastate four square miles and damage a hundred square miles, how many bombs are needed to destroy all of a nation's concentrations of fighting and industrial facilities above ground? Will it be 100, 1,000, or 10,000? That is a question for the military to answer. It has been demonstrated that whatever bombs are required can be produced and delivered to their targets.

Let us try to imagine what may be expected to happen if a war between two major powers should break out in 1970. We may assume that by this time both sides will have such weapons in whatever amount they consider necessary and of greater de-

structiveness and variety than those now possessed by the United States. Because of the enormous advantage of surprise, Pearl Harbor tactics will be employed. Jet-propelled planes or rockets with atomic warheads will be sent without warning at each of several hundred of the enemy's major production centers. No city of over 100,000 population will remain as an effective operating center after the first hour of the war. At least 10 per cent of the attacked nation's population will be wiped out in the initial blow. If this nation elects to fight back, rockets and planes from hidden installations will carry the reply. The attacker in this case can expect no mercy. Though his citizens may have immediately moved underground, his great cities as well as his surface production plants will be annihilated. The fighting will continue until one side chooses to surrender or is unable to resist its opponent's army of occupation.

If the United States should be party to such a war, we should expect Philadelphia, with such neighboring cities as Reading and Wilmington, to follow Hiroshima and Nagasaki into oblivion. With the destruction of these cities we should expect about one out of every four of their inhabitants to be killed. If our nation should eventually win, what would we have gained? Perhaps the control of the world. But of what value would this be with our civilization gone and our population decimated?

No feasible means of preventing the bombs from striking their targets has yet appeared on the horizon. Only two counter measures have so far been proposed. The first is to disperse our cities preferably into hilly regions so that more bombs will be required to destroy them. The second is to place all military installations and essential industries underground and provide

emergency underground shelters for all the population. Clearly such measures will seriously interfere with our normal life. So indeed, was it inconvenient in the middle ages to live in a castle on a hilltop but safety in a world of robbers demanded such a life. Similarly now until positive assurance can be obtained of security through an international military force, we have no alternative but to prepare such shelters and scatter our population. Death is worse than inconvenience.

We must keep in mind that, when all are armed with atomic weapons no superiority of one nation can free it from danger of great damage by another. One man may own a .22 target pistol and another a high-power hunting rifle. But neither is insurance against murder by the other. The insurance is to take away both guns or the fear of punishment by the police, or most surely of all the development of a social conscience for which murder becomes unthinkable.

Is there then any procedure which can free us from the threat of annihilation? I believe there is. It makes however the hard demands of sacrifice of national sovereignty and of faith in other peoples that will give them a share in the responsibility for our own security.

In the statement⁴ issued by the heads of the governments of Great Britain, Canada, and the United States plans are laid looking toward "entirely eliminating the use of atomic energy for destructive purposes and promoting its widest use for industrial and humanitarian purposes." They "emphasize that the responsibility for devising means to insure that the new discoveries shall be used for the benefit of mankind instead of as a means of destruction rests not on our nations alone, but upon the whole civilized world."

⁴ See p. 4 footnote 3.

Let us suppose that the United States, Russia and Britain agree to transfer their own total power to wage international war to a joint Military Commission. It will be better to include France and China as the other permanent members of the Security Council so that the Military Commission can function within the framework of the United Nations Organization. This Commission will have placed under its orders the united armies, navies, and war weapons of the member nations. Its charter will give the Military Commission the responsibility for stopping any armed conflict between nations that may arise, including wars in which the member nations are themselves participants. This responsibility can be carried out since the major nations will have contributed to the Commission all of their own fighting strength except that needed for their internal policing. To be effective it seems obvious that the actions of the Military Commission cannot be subject to the veto power of any single nation but must be controlled by the joint action of some such group as the Security Council. For concreteness we may suggest further that this Commission have its seat in Canada with its headquarters at either Ottawa or Vancouver. Canada will accordingly be the home ground of the combined armies, the home waters of the combined navies, and in its vast territories will be dispersed the atomic weapons of the member nations ready for use in case of emergency.

As thus envisaged the military strength of the Commission would be so great as to make hopeless the effort of any individual nation or group of nations to challenge its power. At first all the strength in atomic weapons would be contributed by the United States. The other member nations would, however, contribute armies and planes and guns according to their proportionate share.

When the agreement is reached to the satisfaction of the member nations the 'know-how' for producing atomic weapons would be passed on to the Commission which these nations entrust with their united military power. From then on there would be no reason why atomic bombs should be made by any other group here or in any other country. Nor is there any reason why, until such an agreement is reached, the technical secrets of atomic weapons should be released from the countries that now have them.

The far-reaching agreement here suggested is perhaps one that cannot be attained at one step. Time will be required to make the needed readjustments of our thinking. But the terrible threat of atomic war which Mr. J. R. Oppenheimer² described so graphically is upon us and makes it necessary for us to make these readjustments before time runs out.

In the exploitation of the peacetime uses of atomic energy each nation will need to give suitable assurance to the others that its own control of its atomic industry is such as to prevent the malevolent development of weapons by any group within its borders. It is essential that such assurance include provision for the inspection to any extent that may be necessary by representatives of the international Commission.

We are thus proposing that international wars be outlawed and that responsibility for preventing wars be placed in an international Military Commission that will act under the direction of the Security Council of the United Nations Organization. This Military Commission with its headquarters perhaps in Canada will monopolize the armed forces of the nations that enter the agreement except those needed for in-

ternal policing Under its supervision atomic weapons will be produced solely for its own use. The member nations will undertake to prevent the illicit production of fissionable materials within their own boundaries and thus will be supported by permitting complete inspection of their activities by agents of the Military Commission.

If the nations follow such a procedure with courage and determination it would seem possible to insure the banishment of international wars It will then be possible to develop with assurance the peaceful fruits of atomic energy

Two alternatives have been suggested to this idea of preserving our safety through an armed international Commission One is atomic disarmament. The other is maintaining our own strength on a conclusively higher level than can be attained by any combination of other nations

I am convinced that atomic disarmament would be a fatal mistake. The proposal we have been discussing calls for the resignation by every individual nation of the right to make and possess atomic weapons but it makes this outlawing effective by placing atomic weapons at the disposal of the United Nations Security Council An agreement to stop producing atomic bombs would only make it possible for some ambitious nation to develop them with the hope of gaining the mastery of the world, and our destruction would be the result.

For a number of years I believe we could as a nation maintain military strength greater than any group that might oppose us Such a policy would, however tend to unite the world against us, which would in the long run be disastrous It is furthermore, doubtful whether over some peaceful decades our nation would continue support of our armed forces adequate to maintain a high level of superiority We should then become

vulnerable to the nation with the long harbored grudge or the newly developed commercial rivalry

The answer is rather to outlaw war itself. And this can be done by a strong world police which has at its disposal more powerful weapons than any recalcitrant nation can hope to acquire.

It is clear however that while working for such an agreement for a united international armed force we, as well as other nations cannot avoid the policy of maintaining our own armed might at a level that will make attack by a potential enemy unprofitable. When our efforts for agreement are successful, our weapons and an appropriate share of our Army will be turned over to the Commission. For the time being, only we are able to produce such weapons and it is our task to see that they are made available for this world police." Thus the Commission will start with the strength necessary to fulfill its responsibilities. If by some mischance the attempts at an agreement should fail, our strength will be doubly needed to discourage attack from any potential enemy.

There is thus real hope that another atomic bomb may never be used in war and, thanks in part to atomic weapons that international war itself may already be obsolete.

THE PEACETIME IMPLICATIONS OF THE RELEASE OF ATOMIC ENERGY

Enough regarding the destructive uses of atomic energy. Of much more interest is its use as man's willing servant. In the long run it can hardly be questioned that the peaceful applications of atomic energy will be those that will most profoundly affect our lives. What these important applications will be is

however as difficult to predict as it would have been a century ago just after Faraday laid the scientific basis for electrical engineering, to tell the future meaning of electricity. At this moment the obviously great field open to atomic energy is that of production of useful heat and power. We also see important though limited medical and industrial applications of radioactive materials artificially produced by atomic chain reactions. Perhaps more significant than either are the new vistas that will be opened up by scientific experiments that make use of the by products of atomic fission.

Such had indeed been the case with such discoveries as x ray. Fifty years ago it was evident that x rays were useful for "seeing" through objects such as the human body, which are opaque to ordinary light. It could not be predicted that x rays would become a powerful weapon in the fight against cancer or that researches made by x rays would reveal the electron and with it give us the radio and a host of electronic devices.

Such unforeseen developments are the result of every great discovery of science. It will nevertheless be worth noting some of the definite practical applications of atomic energy that we can now see clearly before us.

At present, controlled atomic power in the form of heat is in continuous production in large quantities at several plants, especially those at Oak Ridge, Tennessee, and at Hanford, Washington. The heat from these plants is a by-product, and is carried away in the one case by air and in the other by a stream of water. The useful product is neutrons which are used in the plant as a means of transmuting certain chemical elements to others of specially useful characteristics. Of these transmutation processes the most important one is that of uranium into plutonium. Previous to the fission chain reaction

the most abundant source of neutrons was the cyclotron which operates on electric power. Per kilowatt of energy used, the fission chain reaction gives some 10,000 times as many neutrons as a cyclotron, and it is not difficult to make a fission chain reaction plant that delivers 100 times as much power as is used by a cyclotron. This means that right now we are using large amounts of atomic power many times more efficiently for the particular process of producing neutrons than the best electrical machine that we have been able to devise.

Looking to the future, we may expect the use of neutrons as a means of producing new elements by transmutation to become of increasing importance. Plutonium is a concentrated source of available energy and will be a valuable material for peaceful purposes as well as for building weapons.

Other artificial radioactive elements *especially* radioactive ones will also find use in medicine, in industry and in many branches of science. It is yet too early to see clearly how important these uses may become.

We have not yet built an atomic power plant that is generating electrical power. If there were sufficient demand for a demonstration, a reasonably efficient plant using superheated steam for driving a turbine could be put into operation within a year. Before, however, such plants can be made economical competitors with existing practice, a number of years development will be required.

While there are several other possibilities, the most obvious method of producing power from atomic fission is to heat a cooling agent such as air or steam or liquid metal in the chain reactor unit and pass this heated coolant through a heat exchanger which heats the steam for driving a turbine. Beyond the heat exchanger of such a plant everything would be done

according to standard practice. Up to the heat exchanger all the design requires new features, among them protection against the extreme radioactivity of everything, including the coolant that has been exposed to the neutrons

The chain reacting unit itself can assume many forms. The one essential is that it shall contain a fissionable substance such as uranium either in its natural state or if a small unit is desired, enriched with additional U^{235} or plutonium. H. D. Smyth, in his official report,^{*} has described in some detail how this active material can be combined with a moderator such as carbon or beryllium or heavy water so as to bring about the chain reaction

The large atomic power plants now used for producing plutonium have in them many tons of natural uranium and graphite. By using uranium containing more than the usual fraction of U^{235} , chain reacting units have been built that are of much smaller size.

There is however a lower limit to the size and weight of an atomic power plant that is imposed by the massive shield needed to prevent the neutrons and other dangerous radiations from getting out. Next to cosmic rays these radiations are the most penetrating that we know and, for a plant designed to deliver for example, no more than 100 horsepower are enormously more intense than the rays from a large supply of radium or an x-ray tube. To stop them a shield equivalent in weight to at least 2 or 3 feet of solid steel is needed. There are basic laws of physics that make it appear very unlikely that a lighter shield can be devised. This means that there is no reason to hope that atomic power units for normal uses can

^{*}H. D. Smyth, *Account of the Development of Methods of Using Atomic Energy for Military Purposes Under the Auspices of the U. S. Government, 1940-1945* War Department, Washington, D. C. August, 1945

be built that will weigh less than perhaps 50 tons. Driving motor cars or airplanes of ordinary size by atomic power must thus be counted out.

Prominent among the advantages of atomic power are the extraordinarily low rate of fuel consumption and consequent low cost of fuel, the wide flexibility and easy control of the rate at which power is developed, and the complete absence at the power plant of smoke or noxious fumes. With regard to fuel consumption when completely consumed the fission energy available from a pound of uranium is equivalent to the energy obtained from burning over a thousand tons of coal. With the prewar price of uranium oxide at roughly \$3 per pound and of coal at \$3 per ton this would mean the economical use of uranium as fuel if only one part in a thousand of its available energy is used. Actually we should expect the first plants built for producing atomic power to be considerably more efficient than this in their use of the fission energy which would mean a substantial cost advantage in favor of uranium. One must consider also however the need to purify and fabricate the uranium into the desired form. For certain types of power plants under consideration some separated U^{235} is required and this is expensive. Attempting to consider all such factors it appears that the fuel cost of the atomic power plant of the future will nevertheless be small as compared with the corresponding fuel cost of a coal burning plant.

In considering the economic aspects there are, however many other factors. It is not really possible for these to be explored until we have actual experience with atomic power plants. First is the capital cost. Clearly if one must charge against the capital cost what is spent in research and development, this cost is very high indeed. If however one looks down

the line to a billion-dollar-a-year national industry based on atomic power, the nation can afford a considerable investment in the research and development required to bring this industry into being. When this development is completed, it appears not unlikely that the cost of building and maintaining a large-scale atomic power plant may compare favorably with that of a coal-consuming plant of the same capacity.

Much remains to be learned, however, regarding the metallurgical and other technical problems involved in constructing a successful plant to transform fission energy efficiently into high temperature heat. The materials to be used may be expensive. The designs are, nevertheless, essentially simple. An inherent advantage of the atomic power unit is that the heat sources, i. e., the uranium blocks, can readily be maintained at any desired temperature regardless of how rapidly the heat is being removed. This means that a relatively small-size heater unit will be needed and that corrosion due to excessive heating is controllable.

The terrific blasts produced by the atomic bombs have led to unwarranted fear of accidental explosions resulting from the normal use of atomic power. Explosions such as destroyed Hiroshima cannot occur accidentally. Such explosions must be carefully planned for. The dangers of explosions of the 'boiler' type with an atomic power plant are about the same as with a steam plant, which is to say they are practically negligible if the plants are designed and handled by competent engineers.

There is, nevertheless, real possibility of damage to health of the operating personnel from ionizing rays emitted by the plant itself and by all materials that are taken out of the plant. These materials could also become a public hazard. This is the

problem of the health of radium and x-ray workers on a grand scale. That the problem can be solved is shown by the fact that in all the operations of the existing half dozen or more such plants some of which have now been working for years, not a single serious exposure has occurred. This however is due to the thorough inspection and vigilant care given by the health staff. In some of the experimental work we have not been so fortunate. Until we become much more familiar with nucleonics than we are at present, atomic power plants can be operated safely and serviced only with the help of health supervisors who are familiar with radiological hazards.

All this points toward using atomic power first in relatively large units where careful engineering and health supervision can be given. An obvious suggestion is its application to the power and heat supply of cities and of large industrial plants. Within ten years it is not unlikely that the power companies designing new plants for city service will be considering favorably the use of uranium instead of coal for purely economic reasons.

This of course does not mean that atomic power will put coal out of business. Each will have its own field. For small heating units such as the kitchen stove, atomic power has no place. If our national economy grows as it should coal as a chemical agent as for example in blast furnaces and preparation of organic chemicals will increase in importance.

From the point of view of the national economy the introduction of such a new source of power is a clear gain. If it will lessen the cost of heat and power to our cities it will be a stimulus to every industry. If it reduces the pall of winter smoke, it will be a boon to us all. If it gives cheap power where industry

and agriculture need it but cannot now get it, it will extend our economic frontiers. These are possibilities that lie immediately before us.

ATOMIC ENERGY AND OUR WAY OF LIFE

Atomic energy is just one more step along the path of technological progress. It may, however, be the supreme gift of physical science to the modern age. Clearly its value will be determined by the use to which it is put. It is especially worthy of note that, along with other technical advances, the effect of atomic power is to force human society into new patterns. This need for human growth to meet the responsibility of atomic power is the basis of Norman Cousins' striking statement that modern man is obsolete."

Let me note briefly three such effects of technology on society that can be clearly recognized. These are, first, toward greater cooperation; second, toward more training and education; and third, toward evaluating one's life in terms of service rendered to the community.

First, the society that is adapted for survival in the modern world is one in which an increasing degree of cooperation occurs between diverse groups spread over ever larger areas. As an example, consider the atomic bomb project, in which about a million people of all types and descriptions spread throughout the nation worked together to gain a needed result that could be achieved only by a great coordinated community.

In no field is the growing importance of such cooperation more evident than in that of scientific research. Faraday a century ago was one of the first professional scientists. Working by himself he covered the whole field of electricity and much

more besides. Sixty years ago Thomas Edison organized what was perhaps the first research team to work with him at Menlo Park. Now our country has thousands of research laboratories. From 1900 to 1940 our universities developed organized research groups for studying specific problems. Astronomers built specialized observatories. Research centers grew for studying diseases. Teams of physicists built cyclotrons and surveyed cosmic rays over the world. When the war came cooperative research became of greatly increased size and effectiveness.

The development of the methods for producing plutonium is typical. At the peak there were engaged on this one problem roughly 5 000 laboratory workers in more than 70 locations studying its different aspects. Not only theoretical physicists and nuclear chemists were needed. Equally vital were corrosion experts and metallurgists and hematologists and meteorologists, laboratory technicians, mechanics, and office workers of many kinds. No one person could be skilled in every field or understand even the meaning of the answers to the many problems. But somehow the group mind integrates such knowledge into the useful form that results in a process that successfully produces plutonium.

There remains, happily, a valuable place for the individual research man who masters and advances his own limited field of study. His specialty, however, is of little value except as a part of a broader field. More and more we find that even in a limited field a team of men with different specialties working together does the most effective work. New thoughts develop in their discussions. More refined techniques are available. A team which thus supplies a combination of originality and special skills is the pattern toward which research is moving.

Cooperation is thus the very life blood of a society based on

right to live their own lives in the pursuit of happiness without unnecessary restrictions, not primarily the opportunity to shape a better society. Now both capital and labor strive to justify their position in terms of the usefulness of their contribution to society and our nation has fought a war with unparalleled unanimity because our loyalty to the common cause made us ready for any sacrifice.

We have not had in this country prominent movements similar to that in Germany where the youth was whipped to patriotic ardor by the call to lose one's self in the greater good of the state. Nor has any "cause" in this country perhaps met with the wide response the Russians have given to communism as a political system in which each person consciously works for the good of all. Yet Americans respond to many calls to service. As members of scientific societies we are aware of our own increasing attention during the past generation to the social responsibilities of science and scientists. The present active concern of the scientists about the political disposition of the atomic energy problem is apparently only a representative example of the anxiety of everyone in the nation that, with the great issues with which humanity is faced, his own actions may help rather than hinder a good solution. The greater powers placed in our hands by technology seem indeed to make us more acutely aware of our responsibility to use these powers for human ends that go beyond ourselves.

Typical of the forces working in this direction is the recognized need that our form of society must attain its fullest strength if it is to survive in the fierce competition of the post war world. We have come to realize, however, that our strength lies in the many millions of our citizens who are working efficiently and loyally at the nation's tasks. Widespread education,

encouragement of each individual to seek for the place in the game where he can play best, opportunity for advancement and leadership—all these have helped to strengthen our society. Self-preservation demands that all possible effort be given to enable and encourage every citizen of the country to contribute his best to the needs of the nation. To attain this result, cultivation of the spirit of service is of first importance.

The evolutionary law of the survival of the fittest applies to societies as well as to individuals. According to this law the society of the future will inevitably advance along these lines of cooperativeness of education and of individual concern with service toward the common welfare. If selfish interests or an ill-adapted form of government should prevent our growth along these lines some other nation or group that can develop thus more rapidly will pass us by.

You will note that these factors that give strength to society are precisely those that characterize the highest type of citizen. Cooperation—he likes to work with others on a common task. Education—he has learned to do his own useful task and to share intelligently in solving public problems. Service—the central objective of his life is to contribute to the common welfare the maximum that his abilities make possible. These also are the factors that make life of greatest value to the individual himself.

My point is this—the release of atomic energy is merely the most recent important step of that steady progression of science that is compelling man to become human. He must pay careful attention to cooperation, education, and service for the welfare of society if he is to thrive under the conditions that science imposes. If we will let ourselves grow as thus indicated the civilization of the atomic age promises to be the richest that

history has known not only with regard to maternal bounty but also in its cultivation and appreciation of the truest human values

How then are we justified in describing atomic energy as a human asset?

First, atomic energy now supplies for the first time weapons which make it possible for a centralized world government to prevent wars between nations. Having made war intolerable because of its enormous destructive power it thus opens the way for an international organization to prevent war from ever occurring again.

Second atomic energy is now a source of useful new materials produced by transmutation. It promises to supply us with heat and power available in large quantities wherever needed and thus to open new economic frontiers. New advances in medicine, in industry and in science are on the horizon.

Third as the most recent great step in the long progression of advances in science and technology the advent of atomic energy is forcing mankind along the difficult road to greater humanity. Growing cooperation, education and spirit of service are evident trends.

The present is thus a time for hope. True, the atomic bomb has brought us face to face with the fact that continued world strife will mean disaster and death. It is however likewise true, and much more worthy of attention, that the way is now open as never before for the world to reach a true unity with world peace a necessity that can and will be attained.

When our first parents ate of the fruit of the tree of knowledge, they became as gods knowing good from evil. Much as they longed to return to the garden of innocence an angel with a fiery sword stood in their way. Their only hope for peace lay

in work to make the earth give them a fuller life. Somehow the marvel occurred that in their work they became human souls who shared the task of their Creator and came to be called His children

The same angel with the same fiery sword prevents us from returning to a pre-atomic age. We have no choice but to use our great new powers in the effort to build a better world.

In the fierce competition between social systems in the atomic age, the need for strength demands that we enable every citizen to contribute to the common welfare as his abilities may permit. Permanent peace can now be secured if we will work for it. Increased prosperity with broader horizons lies before us. Greater development of the human spirit is the inevitable consequence of the increased responsibility for using our new powers. These are among the greatest of human goods.

CHAPTER II

THE WORLD

WITHIN THE ATOM¹

BY L W CHUBB²

At 5 30 A.M. on July 16 1945 the skies over the desert lands of New Mexico were rent by a terrifying explosion. Its dazzling burst of light was brighter than the noonday sun its heat melted the desert sand and rocks so that they flowed together. A great volcano of dust and debris churned from the desert and seethed high into the sky.

Many miles away behind a heavy barricade, a group of scientists watched with awe. Their experimental atom bomb, perhaps the most important single experiment ever attempted by man was a success. The key to release the almost limitless

¹ This chapter is based on a Westinghouse Little Science Series Booklet and is reprinted by permission of Westinghouse Electric Corporation.

² L. W. Chubb, D.Sc. worked with the atomic bomb project from its beginning. He had been Director of the Westinghouse Research Laboratories since 1930 and had supervised research on hundreds of scientific developments.

power within the atom had been found. Man had entered the age of atomic energy

The story of the search for atomic energy is a fascinating one. It tells of the seeking out of little things so small we can scarcely conceive of them and of huge machines to help in the search. It is a story of simple things like air and oil and fog, and of complicated apparatus like the cyclotron and mass spectrometer. It tells of prying into the innermost secrets of nature, of theories so revolutionary that people scoffed at them, of experiments brilliantly planned and executed, and of discoveries stumbled on accidentally. It is indeed, a typical tale of science.

Man has always wondered about the make-up of the universe. A long time ago before 400 B.C. a Greek philosopher named Democritus was thinking about this problem. He had the idea that things were composed of invisible, indestructible bits of matter. What a remarkable bit of guesswork this was—for 400 B.C.! There wasn't much then that man could do to find out about these tiny particles—if indeed they existed at all. And so for twenty-two centuries very little more was heard about them until an English chemist and physicist named John Dalton came along. Instead of philosophizing about things Dalton performed experiments. These experiments were concerned with the way *elements* combine to form *compounds*.

Dalton's experiments showed that the elements behaved as if they were composed of tiny units or particles. These units of matter Dalton called *atoms*. His theory was that all matter was made of these tiny atoms—that all the atoms of the same element are alike, that the atoms of one element differ from

the mass of the lightest atom hydrogen. Put down a decimal point, then 27 zeros and then the figure 9. This is the mass of the electron in grams.

Today scientists know a great deal about the electron. This tiny particle which goes into the make-up of all matter is the fundamental negative electrical charge. Electrons can do a lot of things. When they stream through a wire, they constitute an electric current, and about 6 billion billion pass through an ordinary 100-watt electric lamp each second. They are the tiny easily managed carriers of current in all radio tubes. They sweep across a cathode ray tube and give us a television picture. They bounce back and forth within an atom and produce light or x rays or other radiations. They are involved in all chemical reactions.

But electrons are not the only particles in an atom. They couldn't be. Atoms ordinarily are neutral, or not charged, so they must have as many plus charges as minus charges. Besides, the electron is only a small part of the mass of the simplest atom. Where is the rest of the mass? Also certain calculations showed that the electron has a diameter only about $\frac{1}{43,000}$ that of an atom. What is in the rest of this space? Man wanted to peek into the atom and see what else was there.

Thomson thought the positive part of the atom made up practically the entire atom itself and that the tiny electrons were stuck around this large positive portion in some way. But how was anyone going to be able to pry into anything so small as an atom? If we could place them side by side, 250 million hydrogen atoms would just about stretch an inch.

Henry Becquerel, a French physicist, chanced upon a way to peer into this tiny world through his discovery of *radioactivity*. He found a strange, invisible radiation coming from



FIGURE 1 Large active prominence 140 000 miles high photographed with the K line of calcium July 9 1917. The small (artificial) disk represents the size of the earth (Courtesy Mt Wilson Observatory)

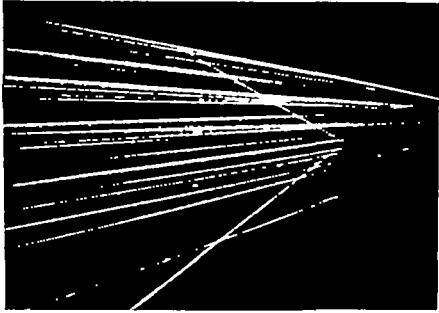
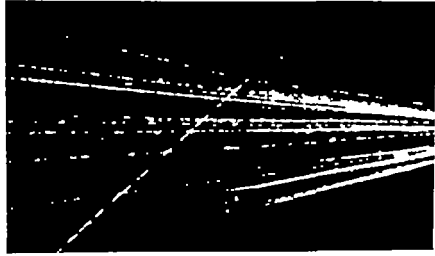


FIGURE 7 In the photograph on the left, alpha particles are shown streaming through a cloud chamber. One has hit a hydrogen nucleus, and since the alpha particle has a mass four times as great, its path is hardly affected at all. But the light hydrogen nucleus is knocked out of the way toward the left.

In the right hand picture, an alpha particle collides with a helium nucleus. These particles are identical in mass, and you can see how they share the energy of the impact and fly off with equal deflections. These photographs were taken in a Wilson cloud chamber. (From Millikan, Gale, and Coyle, *New Elementary Physics*, Ginn and Company.)

compounds containing uranium and he couldn't do a thing to change this behavior one way or another. Others tried. But do what they would, the substances went merrily on their way giving out the invisible radiations.

Where did this energy come from? Energy simply couldn't be manufactured out of nothing—and yet the uranium compounds seemed to be doing just that. Perhaps the source of the energy was to be found in the uranium itself.

Marie Curie was an unknown chemist when she heard about Becquerel's peculiar uranium compounds. With her husband, she decided to analyze them. After three years of difficult, strenuous work they found the answer. The activity was caused by minute traces of a new element—a strange, wonderful element they called *radium*. It was exceedingly rare; they had the merest pinch of it. But what stuff it was! The Curies never ceased being amazed at it. Radium proved a limitless reservoir of energy— $1\frac{1}{2}$ million times more radioactive than uranium—throwing out its energy in all directions and never seeming to run down. Soon more radioactive elements were identified. The scientist pounced eagerly upon them. Perhaps these would help him peek inside the atom because they were conveniently blowing up in his face.

Among the scientists who studied the properties of radium was one of England's greatest physicists, Ernest Rutherford. He wanted to know what sort of radiations were coming from the radium. He found three kinds and called them *alpha*, *beta*, and *gamma* rays.

Soon it was discovered that the whole group of radioactive elements formed a sequence. When a radioactive element blows up and releases some of its energy, it forms a new and entirely different element of less mass. When an element loses

an alpha particle, its mass decreases by 4 times the weight of a hydrogen atom and its positive charge decreases by 2. When the element loses a beta particle, its mass is practically unchanged, because the beta particle is nothing more than an electron. But losing this electron with its negative charge makes the positive charge of the atom increase by 1. Again a new element is formed. In this process of losing alpha and beta particles, uranium changes into elements like radium radon and polonium—and finally ends up as lead. In about $4\frac{1}{2}$ thousand million years uranium is half through its disintegration (this time is called its *half life*) giving off 24,000 alpha particles per gram for each second of its existence.

Now the study of atoms took a big step forward. For the first time, scientists were equipped with bullets—atomic bullets. Why not turn this artillery on an atom and see if its secrets could be blasted out? Rutherford decided to try. It was a strange bit of hunting—shooting invisible bullets at invisible targets. But what bullets! Their speed is so great that if they could keep going they would travel around the earth while you read this sentence. If one of them weighed a pound, it would have the effect of an ordinary bullet which weighed 150,000 tons. So Rutherford started on his shooting expedition and turned the alpha particles on various elements.

One thing was learned right away. Thomson's atoms with a large positive center just didn't exist. Most of the alpha particles would pass right through a substance as though it were not there. Evidently most of the atom was empty space. With millions of shots Rutherford would occasionally get a hit, and the alpha particle would go bouncing off in a different direction. From this information he decided that the positive portion of the atom was a tiny *nucleus* inside it, smaller even than

the electron—so small that if the nucleus of a hydrogen atom could be enlarged to the size of a pinhead the atom itself would be about 30 stories high. And yet in this small speck, 1 millionth of 1 millionth of the volume of the atom, lay all but about $\frac{1}{1836}$ of 1 per cent of the mass of the atom itself. The sun occupies just about as much space in the whole solar system as the tiny nucleus occupies in an atom. How could you identify this tiny speck? Soon the answer was found.

The atomic bullets were turned on the gas nitrogen, and what do you suppose came flying out of the nucleus of the nitrogen atom when an alpha particle smacked into it? Not nitrogen at all, but hydrogen ions—tiny particles of hydrogen with a positive charge of 1. Rutherford bombarded other elements—and out came the same hydrogen ions. Was this the fundamental particle of matter scientists had been searching for so long? Yes here was the answer. The positively charged building block of matter is the nucleus of a hydrogen atom—a hydrogen atom stripped of its single electron. Scientists called it the *proton*.

At last the atom was unfolding. But how were the electrons and protons arranged in an atom? One of Rutherford's students Niels Bohr, a Danish physicist, pictured the atom as a tiny little solar system with the electrons whizzing in orbits around the nucleus much as planets whirl around the sun. The number of electrons in the orbits exactly balance the number of protons in the nucleus to make the atom electrically neutral. Thus the hydrogen atom consists of a single electron traveling in its orbit around a nucleus of a single proton.

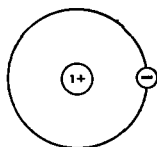
Meanwhile, a brilliant young Oxford University student Henry Moseley had made a significant discovery. When he bombarded the various elements with Roentgen's x rays he

found that they fell into a simple numerical order with the number assigned to the atom being equal to the number of positive charges or protons, in its nucleus. This number is also the number of electrons revolving around the nucleus. It is called the *atomic number* of the element. Hydrogen, with atomic number 1 has 1 proton in its nucleus and 1 electron in an orbit around the nucleus. Also because it has 1 heavy particle in its nucleus the *mass number* and *atomic weight* of hydrogen are both 1.

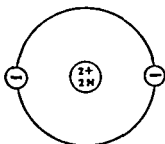
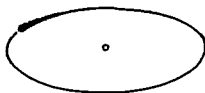
Since helium has an atomic number of 2, it must have 2 electrons in its orbit and 2 protons in the nucleus. But there is something wrong here. Scientists had learned to weigh atoms very accurately and they knew that helium has an atomic weight of 4. Instead of having 2 protons in the nucleus it would seem that helium in order to weigh what it does should have 4. This state of affairs led to considerable speculation. Scientists believed that there must be another particle in the nucleus of the atom—a particle having the mass of the proton but no electrical charge—a particle which increased the atomic weight of an atom without affecting its atomic number.

The experts on atoms searched a long time for the particle, and finally in 1932, James Chadwick, an English physicist, found it. The particle he discovered is called the *neutron*, and it is a fundamental building block in the nucleus of the atom. It is also a very powerful weapon in the hands of scientists who smash atoms.

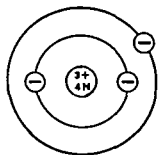
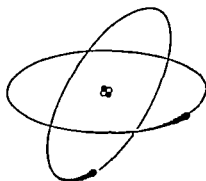
The neutron fits very nicely into the scheme of things. Helium, with its weight of 4 and charge of 2, must have a nucleus composed of 2 protons and 2 neutrons and must have 2 electrons to balance the charge of the 2 protons. Lithium, with an atomic weight of 7 and atomic number of 3, has 3 elec



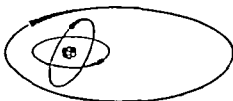
HYDROGEN



HELIUM



LITHIUM



○ PROTON
● NEUTRON

FIGURE 8 As a simple means of representing their structure, atoms are usually pictured with the number of protons and neutrons indicated in the nucleus, and the electrons shown in their orbits around the nucleus (left) The diagrams on the right are a more modern view of these atoms. However, these pictures of the atom have been modified by the discoveries of recent years. No picture of an atom should be taken too literally. Relative sizes and distances cannot be correctly represented, nor can the shape of an atom in space be shown on the plane surface of a sheet of paper. (Courtesy Westinghouse Electric Corporation.)

trons and a nucleus composed of 3 protons and 4 neutrons. This same idea can be applied to all the elements up to the very heaviest natural atom, uranium, with atomic number 92 and atomic weight 238.

The fact that adding or removing a neutron changes the mass of an atom without affecting its charge offers an explanation of another phenomenon which was well known at the time the neutron was discovered. Scientists had found that the atoms of a given element were not necessarily all alike. In most cases the atoms vary in weight. For instance, for a long time it was thought that oxygen with atomic number 8 had an atomic weight of 16 and all its atoms were exactly alike. But in time it was found that some oxygen atoms weighed 17 and a few even weighed 18. However all of them are atoms of oxygen because they all have the same atomic number; they have the same number of electrons and protons and this determines the way they behave chemically. Such varieties of an element are called *isotopes* and most elements have two or more of them.

The year 1932 brought the discovery by Carl Anderson, an American physicist, of a fourth particle of matter, the *positron*. It is a positive electron with the same mass as an electron but with a positive rather than a negative charge. The positron can be observed coming from atoms made radioactive by bombarding them with neutrons. It is a fleeting fellow. Its total existence is a very small fraction of a second, then it unites with an electron and the two bits of matter disappear in a burst of energy.

Matter disappearing as energy? Yes, the behavior of the positron helped establish a fact which scientists had known for some time. Matter and energy are not different things at all,

they are merely manifestations of the same thing. When we say that matter cannot be created or destroyed or that energy cannot be created or destroyed, we must remember that one may be changed into the other. Radium has been doing just this since the world began—converting its mass into energy.

The idea that mass can be converted to energy and energy to mass is not new. More than forty years ago Einstein had worked out a formula for the conversion

$$\text{Energy} = \text{Mass} \times (\text{Velocity of light})^2$$

The amount of energy produced by the conversion of matter is utterly fantastic. For example, if 1 pound of matter could be entirely converted, the energy produced would be equal to that given off by burning $1\frac{1}{2}$ million tons of coal. Such amounts of energy are hard to imagine. Actually a tiny bit of matter is converted into energy in ordinary burning, but the amount is so very small that no laboratory balance can possibly detect it.

But scientists liked to dream of this tremendous source of energy and to speculate about it. And they had figures on which to base their dreams. Consider the 2 protons and 2 neutrons in the nucleus of a single helium atom. The mass of a proton is 1.0076, the mass of a neutron is 1.0089. Therefore, the nucleus of the helium atom should have a mass of $2(1.0076) + 2(1.0089) = 4.0330$. Now the observed mass of the helium nucleus is only 4.0028, which shows a disappearance of 0.0302 mass unit when the neutrons and protons go together. What happens to this mass? It is the *binding energy* of the nucleus—the energy which holds the nucleus together. And it is also the energy required to blast the nucleus apart. The nuclear physicist expresses this energy in a unit all his own—*electron volts*. One electron volt is the energy acquired by an electron when

it falls through a difference in potential of 1 volt. It is indeed, a very small amount of energy. A 10-watt electric lamp in burning for 1 second consumes the equivalent of about 62 billion billion electron volts. The energy represented by the 0.0302 mass unit of our helium nucleus is only about 28 million electron volts, but atoms are so numerous that the binding energy of the atoms in 1 gram of helium is enough to light the lamp continuously for about 2200 years!

The tremendous amount of energy locked in the atom led the scientists to try to release it. The accepted method is to blast the nucleus with all types of particles. Once in a while a nucleus is hit, and changes occur in the atom's structure. These changes can be put into the form of an equation just as ordinary chemical changes are.

In atomics we identify the variety of atoms and atomic particles by a system of abbreviations. The atoms have their usual chemical symbols: hydrogen = H, oxygen = O, nitrogen = N, and so on. However, the symbol O does not tell us which isotope of oxygen is meant. This makes no difference in chemistry because the three isotopes of oxygen are chemically identical. But in physics it makes a great deal of difference, because the three isotopes have different masses, different nuclear composition, and different binding energies. Therefore, we indicate the three isotopes of oxygen as ${}_8\text{O}^{16}$, ${}_8\text{O}^{17}$, and ${}_8\text{O}^{18}$. The subscript at the lower left is the atomic number of the atom and tells the positive charge, or number of protons in the nucleus. The superscript at the upper right is the mass number of the atom and tells the combined number of protons and neutrons in the nucleus.

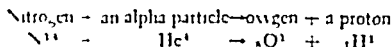
The first of the smashers of atoms was Ernest Rutherford, who is generally considered the father of nuclear physics. We

THE ARTILLERY OF ATOMICS

These are the important particles used in smashing the atom. Their nature, abbreviations, and sources are indicated. Just which particle is used depends upon the atom to be smashed and the results desired.

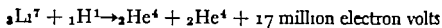
Particle	Nature	Abbreviation	How Obtained
PROTON	Hydrogen nucleus	${}^1\text{H}^+$	Hydrogen ions, produced by the cyclotron or Van de Graaff generator
NEUTRON	Uncharged nuclear particle	on^1	Made by bombarding beryllium or boron with alpha particles
DEUTERON	Heavy hydrogen nucleus	${}^2\text{H}$	Heavy hydrogen ions, produced by the cyclotron or Van de Graaff generator
ALPHA PARTICLES	Helium nucleus	${}^4\text{He}^+$	Helium ions produced by the cyclotron or Van de Graaff generator. Also emitted naturally from radium
BETA PARTICLE	Electron	$-1e^0$	Emitted naturally from radium. Also produced by the betatron

have seen how he bombarded nitrogen with alpha particles and obtained his building block of matter—the proton. Let us look at this reaction:



Here was the dream of the ancient alchemists come true—the creation of one element from another—nitrogen changed into oxygen. Tests soon showed that many elements can be blasted apart by alpha particles. As atom smashing methods improved, huge pieces of electrical apparatus took the place of tiny bits of radium. Particles which were artificially shot at a target replaced those from natural sources.

In 1932 a stream of artificially excited protons was turned on a target of lithium. The unexpected happened! The lithium disintegrated, and for each lithium nucleus two alpha particles, or helium nuclei, came bounding out, and a large amount of energy was released.



Where did the energy come from? Well suppose we add together the mass of the lithium atom and the proton and compare this value to the mass of the two alpha particles. We find the alpha particles have a mass 0.0185 unit less. This amount of matter disappears in the reaction to reappear again as 17 million electron volts of energy.

A new weapon for atom smashing arrived on the scene when Professor E. O. Lawrence, another American physicist, invented the *cyclotron*. This device has grown from a machine not much larger than the human hand to a monster which packs a wallop of about 100 million electron volts and has a magnet, the world's largest, weighing 4,000 tons. The atomic bullets fired by the cyclotron are protons, alpha particles, and another particle called a *deuteron*. The deuteron, or heavy hydrogen nucleus, is the nucleus of a hydrogen atom which has a neutron in addition to the usual proton.

In one experiment Lawrence threw deuterons at rock salt and thereby opened one of the most promising fields of atomic research. By the process he made radioactive sodium—sodium chemically like any other sodium but with nuclei which explode, giving off electrons and gamma rays.

Let us see what happens. In effect, the sodium nucleus absorbs the swift moving deuteron, causing a violent upheaval inside the nucleus. The deuteron breaks up into its two parts,

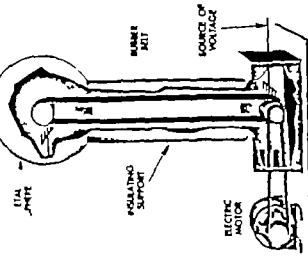


FIGURE 9 In a Van de Graaff generator electric charges from the voltage source are picked off by the endless belt and carried upward to the metal sphere. Because the charges move quickly to the outside surface of the sphere more and more charges can be conveyed to the inside, until a very high electric potential is attained. In one large machine, the spheres are 15 feet in diameter and the supports are 6 feet in diameter and 25 feet high. The rubber belts are 4 feet across and the generator develops a potential of greater than 2 000 000 volts (figures 9 and 10 courtesy Westinghouse Electric Corporation)

FIGURE 10 The 4 000 000 volt atom smelter of the Westinghouse Research Laboratories is one of the largest Van de Graaff generators ever built. One advantage of this type of atom smelter over the cyclotron is that the atomic bullets can be more accurately controlled; another is that the particles are more consistent and can be more easily focused on the target. These factors are important in research where exact critical experiments are carried on. However, the cyclotron produces higher voltages and stronger beams of

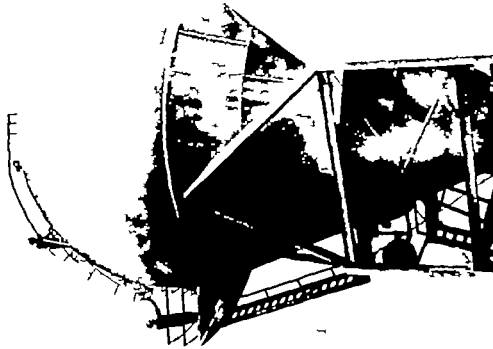




FIGURE 11 This is what happens when an atomic bomb explodes. The photograph shows smoke billowing thousands of feet in the atmosphere over Nagasaki, Japan (Official U.S.A.A.F. photograph.)

FIGURE 12 The source of atomic bullets in a cyclotron is at the center of the cyclotron tank between the two hollow D shaped sections, called dees. Electrons from a filament ionize hydrogen to produce protons (or heavy hydrogen to give deuterons). These are accelerated toward and enter one of the two oppositely charged dees. The dees are charged alternately + and - perhaps ten million times a second by a powerful vacuum tube oscillator. The magnetic field of the electromagnet causes the paths of the particles to be curved. While they are coasting inside the dee, the dees change polarity and the particles emerge and receive a kick into the second dee. This process is repeated millions of times a second. The particles spiral outward, gaining energy as they go and finally emerge at high velocity from the cyclotron window through which the target is bombarded. Large cyclotrons are surrounded by tanks of water 5 feet thick in order to protect workers from stray radiations. Another device the betatron somewhat resembles a cyclotron but uses electrons as the accelerated particles. (Courtesy Westinghouse Electric Corporation.)

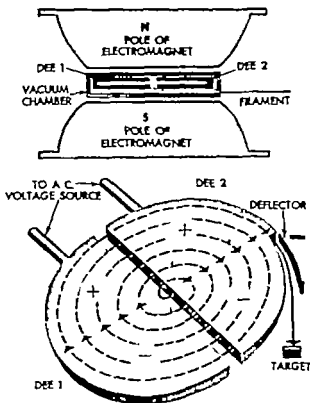


FIGURE 13 This is a photograph taken in a cloud chamber. A neutron is shown blasting apart a nitrogen nucleus. An alpha particle is ejected and scoots away toward the right, and the heavy short line shows the recoil of the rest of the nucleus. The path of the neutron cannot be seen because the neutron is uncharged, produces no ions, and leaves no telltale vapor trail in the chamber. (From Millikan, Gale, and Covey, *New Elementary Physics* Ginn and Company.)



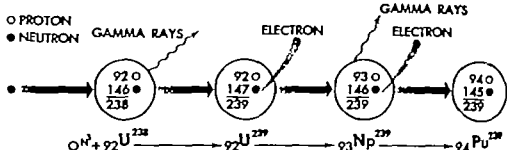


FIGURE 14 Here a nucleus of uranium 238 captures a neutron to emit gamma rays and form a radioactive isotope, uranium 239. This atom then emits a high speed electron to form neptunium 239 which in turn emits gamma rays and an electron to give plutonium 239. Plutonium is considered a stable element, although in time it releases an alpha particle and becomes uranium 235. (Figures 14 to 16 courtesy Westinghouse Electric Corporation.)

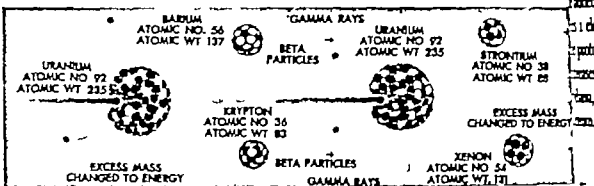


FIGURE 15 Besides neutrons, the fission of a U^{235} nucleus produces two elements of unequal mass which are radioactive for a time but finally become stable. There seem to be several different elements which can form depending on the speed of the neutron causing fission. The elements in the lighter group usually have masses from about 83 to 115 and those in the heavier group have masses from about 127 to 154.

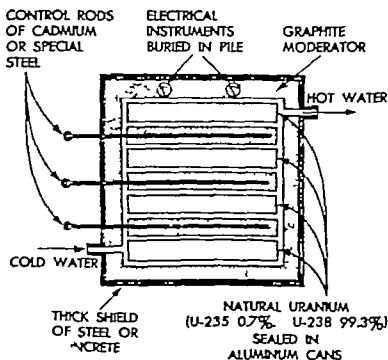
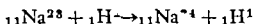


FIGURE 16 A uranium pile differs from an atomic bomb in that the fission of U^{235} is controlled, just enough neutrons are produced to continue a chain reaction. The fission of the U^{235} produces neutrons. These are slowed to the proper speed by the moderator so that they can be captured by part of the U^{235} to form plutonium. The neutrons of U^{239} and Pu^{239} are then removed from the pile and the plutonium separated by chemical means. The pile starts automatically because of stray neutrons or cosmic rays. The control rods readily absorb neutrons, and when they are slid into the pile they take up so many neutrons that the chain reaction is under complete control. The figure shows the essential parts of a plutonium pile.

a proton and a neutron. The proton comes flying out, leaving the neutron behind. This neutron raises the mass of the sodium but does not change its charge. In other words a sodium isotope forms



This isotope is radioactive and disintegrates. We can think of the added neutron as breaking up into its equivalent—1 proton plus 1 electron. The electron is emitted as a beta ray leaving the proton behind. Therefore, the positive charge on the atom increases by 1 and when this happens we no longer have sodium but the element next higher in atomic number magnesium



Since 1934, when artificial radioactivity was discovered more than 500 radioactive isotopes have been formed, and almost every element is now known to have one or more of them. An interesting thing about this is that man has been able to make more different kinds of atoms than he has ever found in nature.

Artificial radioactive elements offer great possibilities in medicine. The advantage of using them is that they can be tailored to order. Such an element can be taken into the body where it gives off its beneficial radiations and in a few hours or days depending on the element, its life is over and no harm is done to healthy tissue. If radium is used for deep-seated cancer treatment, the radium must be removed because it gives off radiations almost indefinitely and would soon cause death from overexposure.

Another nice thing about the artificially radioactive elements is that they are chemically the same as the usual form of the

element. Hence they can be injected into the body where they act in a normal manner except that they emit their beneficial radiations. For example, radioactive phosphorus might be used in the treatment of leukemia, a disease caused by the cancer like growth of the white blood cells. Phosphorus is normally present in the bones and if the radioactive variety is deposited there, it will attack the excess white blood cells at their source, the marrow of the bones.

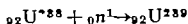
The smashers of atoms soon found that the neutron was a very effective atomic bullet, because it is heavy and has no charge. A neutral neutron enters a strong positively charged nucleus much more easily than a positive particle, such as a proton or alpha particle. But because neutrons have no charge, they are hard to handle. They cannot be hurled by a cyclotron. The best we can do is to use protons, deuterons or alpha particles to bombard a material like boron or beryllium, knock some neutrons out of them and thus obtain our neutrons secondhand.

Little can be done to control these neutrons once they are produced, because they are unaffected by electric charges or magnets. Another thing is unusual about them. The neutrons do a better job of causing certain nuclear changes if they are slowed down, and just what they do depends a great deal upon their speed.

Enrico Fermi, one of the most famous of present-day atom smashers, as early as 1934 turned neutrons on the heavy elements. These bulky atoms already have unstable nuclei which blow up of their own accord. What would the neutrons do to them? The heaviest element, uranium, gave surprising results by changing into a new element.

We now know that when a neutron is slowed to the correct

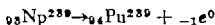
speed, the uranium nucleus snatches it up and forms a new heavier isotope.



Now this new form of uranium is unstable and begins to give off electrons, and when it does something happens. The atom turns into a new element—a man-made element never before known to exist—element number 93. The element is named *neptunium*, Np.



But that is not all. Neptunium is not stable either. It also gives off an electron and turns into another element still higher in atomic number. This is another brand new man-made element—number 94, its name is *plutonium*.



Plutonium seems to be satisfied, it is fairly stable and behaves itself until you start shooting neutrons at it. When you do that, the plutonium literally blows itself to pieces. It splits into atoms of smaller atomic weight and releases vast quantities of energy. This splitting process is called *nuclear fission*.

Plutonium is not the only atom which undergoes fission. Indeed, the process was discovered in one form of uranium in 1939. Soon uranium was being cracked open in atom-smashing experiments all over the world. These experiments always showed the same thing. When a neutron blasted the nucleus apart, two hundred million electron volts of energy came pouring out as a result of the annihilation of a small bit of the atom's mass.

And then there was something else. In addition to the frag-

ments of lower atomic weight, the fission produced more neutrons. Immediately the same thought came to the minds of the scientists. Could these newly released neutrons be used to blow apart more uranium to produce more neutrons to blow apart still more uranium and so on and so on? The results of such a *chain reaction* would be obvious—a source of power for one thing, an atomic bomb for another. But then the blackout of World War II settled over the laboratories of the world, and the scientists set to work secretly feverishly to find the answer. All of us now know the result. In America we found it first.

The story of the making of the atomic bomb is one unprecedented in human history. The problems to be overcome seemed too great to solve. In the first place, even though 200 million electron volts is a tremendous amount of energy for the amount of matter releasing it, it is not much energy even when compared to that from a burning match. Millions upon millions of fissions must occur each second in order to have the slightest amount of usable energy.

Then too it is not ordinary uranium which explodes with such violence. The common kind of uranium has a mass of 238 (U^{238}) but it is a scarce isotope having a mass of 235 (U^{235}) which undergoes fission. Only $\frac{1}{138}$ of ordinary uranium is U^{235} and it is difficult to separate from the U^{238} . Remember these are isotopes chemically identical, and one cannot be separated from the other by any known chemical method.

Using the *mass spectrometer* the first tiny bit of U^{235} was obtained in 1940. How much? At the rate then achieved it would take nearly twelve million years to get one pound. How much was needed for a bomb? Calculations showed a minimum of about 2 pounds and a maximum of about 200 pounds. Methods certainly had to be improved. And they were. By the

end of 1943 an entire plant was in operation for the separation of U^{235} by this same electromagnetic method.

There are a number of other ways of separating U^{235} . One of these, the gaseous diffusion method became practical, and by 1945 a large plant for this type of separation was in operation. Here the two isotopes are changed to gases and are allowed to diffuse through a porous barrier where the lighter U^{235} passes through faster than the heavier U^{238} .

Yes separating U^{235} from U^{238} is difficult. Early in the race for the atomic bomb no one could tell if it ever could be done on a large enough scale. It was natural then for scientists to think about the new atom they had made plutonium for they knew that it, too could be split. Plutonium forms when an atom of U^{238} captures a neutron and U^{238} is fairly plentiful. Perhaps there was some way to create plutonium on a large scale.

A long series of experiments showed how to do it with a large mass of uranium and graphite called a *pile*. It is tricky and very dangerous work. The gamma rays neutrons and other radiations which escape from the pile are death-dealing so the pile must be built behind several feet of concrete and steel. No one dares approach an unshielded pile; even the air around it becomes radioactive and poisonous. Then too there is danger the pile may explode with disastrous results. Unbelievable amounts of heat are generated by a pile, and some method of cooling it is necessary.

Then there is the problem of separating the Pu^{239} after it has been formed in a pile. It is done chemically—all by remote control behind thick protective shields until the plutonium is pure.

Of course, there were other problems—thousands of them

But although by the end of 1942 there was in existence only 500 millionths of a gram of plutonium by 1945 a large plutonium plant was in operation producing the material on a commercial scale

More than 4 square miles 60 per cent of Hiroshima, Japan, was blown off the face of the earth on the morning of August 6, 1945—all by a single bomb from the change of a small bit of matter into seething, undiluted energy They tell us in simple, cold figures that the early bombs were inefficient and have already been improved upon Only about 1 tenth of 1 per cent of their active mass was changed into energy For every pound of U^{235} which exploded 0.999 pound of material remained, and only 0.001 pound of the mass was converted into energy If the entire pound of U^{235} (or any other mass) could be changed into energy $11\frac{1}{4}$ billion kilowatthours would result—power equal to that from the burning of about 3 billion pounds of coal or 200 million gallons of gasoline.

Until now man's world has been an electron world. His available sources of energy have been associated with those tiny particles of matter spinning in their orbits in the atom. But now his world will be, at least in a sense, a nuclear world, with the boundless energy locked within the atom becoming available. We are faced with the greatest challenge of all time. Will we use this power to blast civilization from the earth, or will we learn to apply it usefully in a world where each of us is the next-door neighbor to everyone else? Whether we are ready for it or not, a new age is dawning for mankind.

CHAPTER III

ATOMIC ENERGY IN INDUSTRY AND THE PHYSICAL SCIENCES¹

BY SAMUEL K. ALLISON²

INTRODUCTION

BECAUSE OF the misgivings concerning the international situation the applications of atomic power to industry and the physical sciences are being delayed. The fear that other countries will develop atomic weapons before any reliable plan is worked out to insure world peace is holding up the dissemination of information necessary to peaceful atomic developments.

There are fundamental concepts which any investigator anywhere, if he does not make a mistake, can discover for himself. It is my belief, and the belief of many scientists, that that in

¹ From *Occupational Medicine*, Vol. 2, November, 1946. Reprinted by permission of American Medical Association.

² Samuel K. Allison, Ph.D., is the director of the Institute for Nuclear Studies at the University of Chicago. He is a member of the National Academy of Sciences and received the Medal for Merit in recognition of his services during World War II.

formation should be widely disseminated. It is distinct from information on the art of making a bomb or using the new force destructively. This last is a technologic development, which it would be useless to give out at the present time, since it is only a method of using atomic power for evil purposes.

In the past, I have been rather critical and rather vocal about the slow rate at which fundamental information is being allowed to circulate and to be made available. I am happy to say that I believe there are signs that this situation is improving and that the fundamental properties of nuclei and atoms which are scientific entities that any one can discover will be released more rapidly than in the past.

Another difficulty is this. A prominent feature of the legislation which has been passed is the provision that the technique of the development of atomic power for industrial purposes is not to be shared with other nations until Congress, by joint resolution, declares that ample international safeguards have been provided against the destructive applications of fissionable materials. This means that the technique of such industrial uses will have to be developed in secret, and hence more slowly than otherwise.

Another factor is the shortage of trained personnel. During the war the United States stopped training physicists and used what it had. A large number of men believe that they can best serve by returning to the universities and training young men in nuclear physics and chemistry. This return is made easier by their disinclination to work under the burden of compartmentalization of information and secrecy.

Progress however is being made, and the outlines of future developments are becoming clearer.

ATOMIC ENERGY IN INDUSTRY

The feasibility of atomic power as a supplier of electricity to cities and industries will be the issue which will decide the scale of the program for the next few generations. If such power is widely used, the scale of the development will be vast; if it is an unsuccessful competitor with coal and water power because of cost or increased industrial and civil hazards, then a few chain-reacting piles will be operated for military purposes and for the preparation of substances of importance in science and technology.

The physics and technology of the present chain reactors indicate that one of the first industrial applications will be the erection of large power plants operating on atomic fuels and generating electricity for distribution to towns and factories. The most recent estimates of costs indicate that electricity from atomic power will be more expensive, in regions where coal is readily accessible, than from the conventional coal burning installations. Such estimates of costs are extremely difficult to make, and the fact remains that the transformation of 240 tons (217 728 kilograms) of uranium into fission products releases energy equivalent to the burning of 660 000 000 tons (598 752 000 000 kilograms) of coal. One cannot laugh off that figure, and it is power to conjure with. 660,000 000 tons, by the way, is approximately the amount of coal consumed annually in the United States. Yet 240 tons of uranium could be set on one corner of the ordinary speaker's platform.

The whole question of feasibility is tied up with questions of industrial and civic health. It is now well known to the

public that heavy shields must be built around chain reactors developing power in order to protect plant personnel from injurious radiations and that these heavy shields seem to make impossible the development of light, portable power plants. It is just possible that in extremely large, extremely long-range aircraft, the present heavy fuel load could be replaced with a shield around a reactor, and that thus atomic power could be used in flight. But, in my opinion there is no indication that short-range airplanes can be operated with atomic fuels as they are known today

Propulsion of ships with atomic fuels seems technically much more feasible, because the weight of the object to be transported is a secondary factor in transportation by ship

One of the technically simplest applications of an atomic reactor would be to produce large quantities of low temperature heat for chemical or metallurgic industries

Along with all these developments will go the development of industrial health protection. The invisible nature of hazardous radiation and the lack of any sense by which one may detect the presence of radiation are formidable obstacles to be overcome. The plant operators must not only be adequately protected but must also be psychologically convinced of this adequacy. Otherwise, entirely baseless fantasies of injuries from radiation will be developed. It has already been seen that in the war arc welders on the ships developed fantasies that their reproductive powers were being injured by ultraviolet rays, which, of course, was an entirely baseless assumption

Civil populations must be protected against radioactive dusts, radioactive gases and contamination of their water with radioactive wastes from the plants. The public must be edu

cated concerning these hazards so that they will be intelligently understood and not the subject of hysterical delusions

Uranium compounds are poisonous in the more conventional sense. Beryllium and its compounds seem destined to play an important part in atomic energy and experience during the war has shown the toxicity of beryllium dusts especially beryllium fluoride. It is probable that industrial applications will be found for polonium which can be made in the piles and which can be produced as a byproduct of the chain reactors. Its metabolic chemistry must be studied, and its radioactive toxicity guarded against. Many steps have been taken in this direction.

THE USE OF PRODUCTS OF THE CHAIN REACTION IN SCIENCE AND INDUSTRY

Neutrons are an essential link in the chain reaction. As a matter of fact it is the neutrons from fission which diffuse through the fissioning material and cause successive disintegration. It is the electrical, uncharged nature of the neutron which makes the carrying on of the chain reaction possible.

There are now available, throughout the large volume of a chain reacting aggregate, a total number of free neutrons which vastly exceeds anything previously produced. Streaming from apertures in the protective walls around the structures come beams of neutrons in which the total flux is enormously great. The most subtle properties of neutrons previously not successfully studied because of low intensity are now under investigation. Some of these are their lifetime magnetic properties and their diffraction by crystals. In the latter a striking

confirmation is obtained of the theory of the duality of corpuscle and wave, since the gross features of the diffraction closely resemble that of roentgen rays

Indirectly the chain-reacting piles and the atomic bomb have stimulated every branch of nuclear science, whether or not the subject being investigated seems to lead directly to the large scale release of nuclear energy. Funds are available for experimentation on a scale previously unavailable to the average physicist. Two machines each capable of accelerating particles to hundreds of millions of electron volts of energy are being planned for the vicinity of Boston alone. Attempts are being made to produce mesons or particles of mass intermediate between electrons and protons. Mesons at present, are found only in connection with cosmic rays and in such small concentrations that it is tedious to obtain precise information concerning them. If there are neutral mesons, there may be other meson chain reactions which may or may not produce the spectacular results which the neutron chain reaction has already shown.

As physicists experiment with these, they will need health protection. Workers in the pure sciences were notoriously careless about health and accident hazards. For many physicists, the first time they had ever encountered health control and safety engineering was in their association with companies such as duPont, Tennessee Eastman, Union Carbide and Carbon and Monsanto during the war. At first inclined to scoff they learned to respect, if not to admire. The tragic deaths of two physicists at Los Alamos, New Mexico, during experimentation with materials for bombs drove the lesson home.

Although the protection of research workers as an enterprise

will never reach the vast size of the industrial health problem, many of the techniques which will ultimately spread through industry will first be developed on this smaller scale.

The new elements produced by the chain reactors are substances of great scientific interest. The most publicized of these is plutonium which, in the periodic table, is element 94. Other transuranic elements which are now known are 93 neptunium 95 americium and 96 curium. In order to be found in nature in other than tracer amounts an element must have at least one isotope of age comparable with that of the earth, or like radium, be continuously reproduced from such a source. If these transuranic elements ever existed in nature, they have died on earth and now are artificially recreated with the aid of the chain reaction.

One can imagine how a chemist must feel when an element which was extinct is now presented to him for experimentation. I can imagine how a zoologist would feel if a dinosaur walked into the laboratory and submitted himself for dissection. The exact analogy of this phenomenon is in the chemical laboratories at the present time. New elements are being built for the chemists and they are studying their properties.

Other elements, lighter than uranium are missed in nature, probably for the same reason. Elements 43 (technetium) and 61 (promethium) have been artificially recovered from the chain reaction and their chemical properties will now be studied.

Other means are now available for the production of elements 85 (astatine) and 87 (francium) the study of which will enrich the science of chemistry.

About four hundred and fifty radioactive forms of the natural

elements are known and most of them can be produced from the chain reaction

Emitters of penetrating gamma radiation can be produced in the chain reactors and will soon be distributed. A form of cobalt, living about five years and an antimony of sixty days life are prominent among these. Point sources of these can be prepared and used for radiologic examination of broken parts of men and machines. It does not seem probable that these will displace roentgenographic installations in permanent hospitals or factories. However for emergencies in remote locations for instance, where the patient cannot be transported to the hospital a minute capsule of these substances can be flown to the spot for diagnosis or treatment. This of course, can in considerable measure be done with radium today. The artificial emitters of gamma rays will be cheaper more abundant and more versatile, in that the energy of the gamma rays and the lifetime of the emitter can be selected to suit the demands of the case.

The radioactive isotopes which are being produced are mostly emitters of beta rays. Physicists will use them to study the beta ray-emitting process and to look for the neutrino or little neutron a strange particle the emission of which seems necessary to conserve energy and momentum in nuclear disintegrations. They are emitted in vast numbers from the piles but, since they are elusive, little direct evidence of them is at hand, if these neutrinos exist. They are even more elusive than a filtrable virus.

The radioactive isotopes will have many uses in chemistry. When a uranium atom breaks in two by fission the fragments are radioactive forms of elements in the center of the periodic table. The pressing problem of chemical separation of plu

onium from uranium and from these lighter elements produced a veritable rebirth of inorganic chemistry during the war and the new stimulus to that subject will long remain. When a radioactive form of an element is available, it means that a method exists of detecting an exceedingly small amount of it—in many cases only a few million atoms are sufficient. Furthermore, one can follow these very atoms through a series of chemical reactions always keeping track of exactly where they are. Their chemical properties are, to a high order of approximation identical with those of the natural elements which they represent. The application of such methods to problems such as the solubility of insoluble substances the fractionation coefficients between solvents the miscibilities of liquid and the vapor pressures of the so-called involatile substances is obvious and they are already under way.

In industrial technology corrosion studies will be aided, and the detection of minute amounts of dusts and smokes made easier. Processors of precious metals may make them slightly radioactive and make it impossible to carry them out through the exits without ringing an alarm.

RADIOACTIVE CARBON

At the present time it seems that the substance which will most profoundly influence research in the life sciences is radioactive carbon. This long-lived carbon of atomic weight 14 was discovered in tracer amounts with the use of the cyclotron shortly before the war. Now it will be possible to prepare grams of the material. An associated project of considerable magnitude will be the preparation of complex organic chemicals in radioactive form. It will, of course, be possible to prepare or

ganic substances in which specific and known parts of the molecule contain the radioactive carbon, the rest of the molecule being inert.

For certain organic substances such as serums, opiates, and dyes it may be best simply to use animals or plants as the synthesizing agents. Farms may be operated in which the fertilizers and foods will be radioactive, so that radioactive anti-tetanus serum can be obtained from radioactive horses and radioactive opium from radioactive poppies. Radioactive bacteria may be produced also.

Radioactive carbon is an emitter of low-energy electrons, and this has both favorable and unfavorable consequences. Favorable consequences are that, as radioactive substances go, it is not extremely dangerous to the investigator and that in therapeutic applications the radioactive effects will be limited to the tissues immediately surrounding the point of application or absorption of the material. A somewhat unfavorable consequence is that the detection of the presence of radiocarbon and estimation of the amount of the radiocarbon present in a preparation are somewhat more complicated than with substances emitting more energetic radiations. Many mistakes in its use as a research tool are to be expected before the technique of detecting it becomes as widely known and standardized as for instance, nitrogen analysis or blood corpuscle counting.

At the present time, nonradioactive forms of oxygen or nitrogen are known which live long enough to make them useful in general, as research tools. Labeled forms of these elements can be supplied which are not radioactive and the presence of which must be detected by a mass spectroscopic analysis. These are O^{18} and N^{15} . A labeled, nonradioactive form of carbon C^{13} is also being produced. This can be used, together with

C^{14} for instance, in a complicated organic molecule; one part may be tagged with C^{13} and the other with C^{14} and as the molecule breaks up in further chemical or biologic processes the two parts may be simultaneously traced.

CONCLUSION

Many of us who have looked forward to such applications *for months and years are impatient at the delays in acquiring momentum*. We should remember that we are in the back wash of the greatest war effort this country has ever made and that the country is trying to reconvert to peaceful ways at a time when many persons consider that such reconversion is hardly justified in the light of the troubled state of the world particularly the reconversion of the atomic energy project.

CHAPTER IV

INDUSTRIAL APPLICATIONS OF RADIOACTIVITY¹

BY M. BLAU AND J. R. CARLIN²

QUANTITY PRODUCTION of radioactive isotopes as a byproduct of the uranium pile has stimulated interest in older industrial applications of radioactivity and has resulted in many new applications. Radioactive materials are available abundantly now at reasonable cost, and handling techniques have been safely standardized.

Prewar uses for radium in radiographic cylinders as neutron sources (radium-beryllium) in luminous compounds for dials and as static eliminators now become economically attractive to a great many industries. The last mentioned application in

¹ From an article in *Electronics*, April, 1948, reprinted by permission of McGraw-Hill Publishing Company, Inc.

² Dr. M. Blau is at present engaged in the field of atomic energy research at Columbia University and was formerly with the Canadian Radium and Uranium Corporation. Mr. J. Carlin is employed by Tracerlab, Inc., Boston, Mass.

particular merits reconsideration today for all equipment having static problems

INDUSTRIAL STATIC ELIMINATORS

Operation of an industrial static eliminator is based upon the high ionizing power of alpha particles. These have the highest specific ionization power of all radioactive radiations; a single alpha particle can produce about 40 000 ion pairs per centimeter along a path in air, with the exact number depending upon the velocity of the radiation.

Near sources of alpha particles air loses its insulating properties and becomes conducting, dissipating any accumulation of static electricity in near-by objects. The quantity of static electricity that can be eliminated within a certain time interval depends only on the intensity of the alpha radiation present.

The ionization effect of an alpha particle source is limited to its range, which is about 7 centimeters for the fastest group emitted by radium and its decay products. If the ionized air is in movement, however, as will occur in the vicinity of machines in operation or with vehicles in motion, the ionized air is transmitted appreciable distances.

Advantages of radioactive static eliminators include absence of harmful effects on commodities such as are sometimes caused by humidifiers used for the same purpose, and absence of high voltages and sparks that in themselves are fire hazards and inherently dangerous.

Since alpha particles are easily absorbed, it is necessary to apply the radioactive material in the form of a thin layer that does not introduce in itself any appreciable self absorption. The

preparation of these foils is complicated by the fact that it is necessary to retain the gaseous radon product of radium within the foil, since the escape of this gas would signify a loss of active material and create a health hazard. The total alpha activity is due to the decay products Ra A, radon and Ra C, as well as to radium.

Polonium may be used instead of radium as an alpha-particle emitter. It is a pure alpha radiator with no penetrating gamma radiation hence large areas of polonium sources can be used without introducing health hazards. However the short half life of polonium makes it necessary to replace this type of static eliminator after a certain time interval. Other pure alpha radiators having longer half life are not yet available, but these elements may be ready for industrial purposes in the near future.

One millicurie of a radioactive element represents the quantity of this element that emits the same number of particles per second as 1 milligram of radium (3.7×10^7 particles). The ionization current produced by 1 milligram of radium is about 2×10^{-6} ampere and that from 1 millicurie of polonium is 4.4×10^{-7} ampere at saturation voltage. The current from radium is greater than that from polonium because the Ra foil has additional radiation decay products.

Saturation voltage is the voltage necessary to draw all ions out of the field immediately upon formation, so that no losses occur through recombination. The field strength is about 250 volts per centimeter for 100 micrograms of radium or 500 microcuries of polonium coated on one square inch of radioactive foil. Therefore, the formation of 2×10^{-7} coulomb per second can be easily dissipated by these amounts of radioactivity. This accumulation of static, if not dissipated, would

lead within 1 minute (assuming a capacitance of 20 micro-microfarads per square inch) to a voltage of about 600,000 volts clearly a potential danger

The more recent applications of radioactivity in industry may be divided into four groups (1) applications utilizing the ionization power of the radiation, (2) applications utilizing penetrating properties (3) devices in which motions or displacements are detected by radioactive substances coupled by some means to these movements (4) applications based upon the easily recognizable radiations and their detection methods such as tracer methods

Only the first three groups of applications will be taken up here, since the fourth would require quite an extensive paper by itself.

USING IONIZATION POWER

The ability of alpha or beta-emitting radioactive substances to ionize gases or air is utilized in a radioactive resistor the terminals of which are the electrodes of an ionization chamber arranged as in Figure 1

One electrode is covered with a radioactive alpha-particle emitting substance, and the other is connected to an electrometer or amplifier. As the voltage between the electrodes is increased the ionization current will increase correspondingly until saturation is reached, as shown in Figure 2, when all the ions are being drawn to the electrode upon formation. If voltage is still further increased ionization by collision occurs and the current increases as in an avalanche

The initial linear portion of Figure 2, called the ohmic region lends itself to the construction of resistors distinguished

by complete absence of polarization and temperature deficiencies. It is true that the outside pressure if the chamber is not hermetically sealed, or the outside temperature, may somewhat

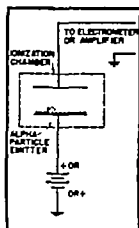


FIGURE 1 Elemental ionization chamber

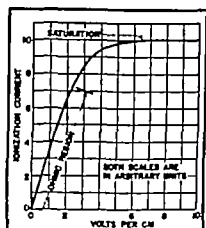


FIGURE 2 Typical ionization characteristic curve of radioactive resistor

influence ionization current, however this influence is small, completely regular, simple to compute, and easily compensated for.

Radioactive resistors have long been used as leakage resistors of electrometers in radioactive laboratories. They are equally useful in electronic circuits requiring high values of grid resistance; the higher the resistance value, the less radioactive material is needed. By varying the distance between the electrodes or varying the number of ionizing particles with diaphragms or other means a single unit may well serve for several ranges and purposes.

Radioactive resistors remain substantially constant in value if the radioactive material used has a long half life, as does uranium or radium. The decay characteristic of materials with

short half life permits construction of decaying radioactive resistors which increase in resistance as they age. These make possible the longer use of relatively shorter living radioactive material in electronic circuits. Decaying radioactive resistors are connected to counteract circuit changes produced by decay of the main radioactive material.

For instance, if polonium with a 140-day half life is used in the main ionization chamber of a radioactive instrument, plate current decreases 0.5 per cent per day. Normal means for compensation by lowering the position of the operating point on the characteristic curve of the first amplifier stage does not restore completely the original conditions. With a polonium resistor in the grid circuit, however, decay of its activity increases the grid resistance in such a manner that the plate current remains constant. The limit of the usefulness of decaying radioactive substances is then determined only by the leakage current of the insulating material employed. The same method can be used with any other natural or artificially radioactive elements.

RADIOACTIVE ELECTROSTATIC VOLTMETER

The radioactive resistor can also be used for measuring high voltages. It will be especially useful where only a small current can be drawn from the source.² By varying the quantity of emitted radiation or the distance between the electrodes a wide range of voltages can be covered. The ionization current, which is proportional to the applied voltage in the ohmic portion of the characteristic curve, can be measured by means of

² L. Goldstein and F. Perrin, Condenser Resistor U. S. Patent 395623

amplifiers. Measurements should be made over two ranges to insure against using a reading corresponding to saturation current.

The degree of static electricity accumulated on parts of a machine can be determined by means of a metal strip coated with a radioactive alpha-particle emitter. The strip is placed near a part of the machine where an excess of charge might lead to fire hazards or any other undesirable event, and is connected to the grid of an electronic tube or directly to a sensitive galvanometer. The metal strip should be well insulated from the ground.

Radiation intensity and distance between activated metal foil and machine are so chosen that under normal conditions the ionization current is zero (ohmic region) or is balanced to zero by a compensating circuit. Any increase in current warns the operator of danger by light signals or an appropriate meter. If the intensity of the radioactive source is great enough or if sufficient amplification is used, it becomes possible to operate a relay that will stop the machine automatically.

The ionizing power of radioactive radiations, especially those of alpha particles, is utilized in discharge tubes to lower the sparking potential or to dissipate space charge.⁴ These applications use either the direct radiation or the light effect due to fluorescent compounds activated by the particle radiation. While relatively great quantities of radioactive materials are necessary to change the discharge appreciably, stabilization and reproducibility of existing conditions can be obtained with small amounts.

⁴ L. Gokstein and F. Perrin: Cold Cathode Gaseous Discharge Tubes. U. S. Patent 511398.

RADIOACTIVE LIGHT SOURCES

As soon as great quantities of radioactive materials become available at decreased prices innumerable applications will present themselves. Light sources of various colors requiring no battery or power line connection can be produced by bombardment of fluorescent compounds with radioactive radiations. The life of these sources will depend upon the half life of the radioactive element and the stability of the luminous compound.

A radioactive light standard has already been developed^{*} using radium as a constant radioactive power source. The fluorescent compound is exposed to the radiation only during short intervals (the radium foil can be easily removed) hence does not suffer any change.

The inherent constancy of radioactive light standards has one application as a radioactive pyrometer utilizing the known principle that the brightness of certain fluorescent substances irradiated with alpha particles varies inversely with temperature. This effect is illustrated in Figure 3 for a polonium preparation serving as alpha source and a special short persistence type of zinc sulfide serving as the fluorescent material. Light emission ceases at a temperature of about 150° C for this material, but other compounds are available for higher temperature ranges. The method lends itself to control of the rate of temperature change in tempering processes. The same effect is produced by x rays or ultraviolet light, but a radioactive source gives constant output along with freedom from servicing.

^{*}M. Blau and I. Feuer. Radioactive Light Standards, U. S. Patent 686704.

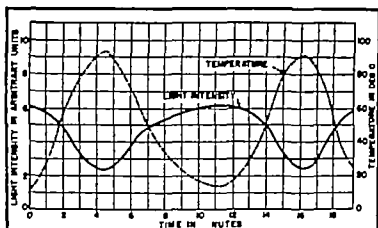


FIGURE 3 Variation in light output of luminous compound with temperature during exposure to constant radioactive source.

RADIOACTIVE CATHODES FOR TUBES

III vacuum tubes artificially radioactive substances can serve in place of heated cathodes with such advantages as constancy of emission and uniformity of energy. The emitted beta particles carry electric charges and hence can serve in place of electron beams if radiation density is sufficiently high. If the beam of beta particles is concentrated by electric or magnetic methods, high electric charges can be accumulated or heat and light effects can be produced.

Gamma radiation has long been used in industrial radiographic work. More recently neutrons are being used for measuring thickness and density of heavy materials and checking uniformity and beta particles are being used for examining light atomic substances.

APPLICATIONS USING PENETRATING PROPERTIES

A scanning device for testing homogeneity and thickness of films during production utilizes beta radiation from Ra B and Ra C plaques. In these, a highly concentrated radium compound is airtight-covered by a thin metal foil in order to permit a maximum output of beta radiation. The beta radiation may also be obtained from an Ra E plaque, which uses an Ra D source in equilibrium with its decay products and covered with an extremely thin metal layer in order to absorb the alpha particles of polonium since they are not needed.

The scanning device uses a decay-compensating method. The beta radiation penetrating a standard film is compared to that

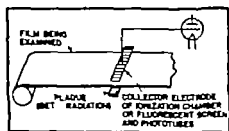


FIGURE 4 Radioactive thickness gauge for moving sheets.

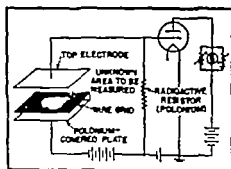


FIGURE 5 Radioactive area measuring device

going through the sample film. The emergent radiation can be measured directly by the ionization effect produced in two identical ionization chambers or indirectly by phototubes responding to the light effect produced on fluorescent compounds as indicated in Figure 4. With highly explosive mate-

nal where even the smallest currents must be avoided, the light effects can be compared by visual methods

Beta radiation can also be used efficiently in comparative methods for measuring changes in composition of organic liquids in tanks or inaccessible locations. The absorption coefficient of beta radiation is relatively high compared to gamma radiation so that even slight changes in density are easily discernible.

The range of alpha particles in solid matter is only of the order of 100 microns precluding examination of thick materials but these alpha particles are extremely useful in detecting the presence or absence of even the smallest quantities of solid matter in space. The radioactive integrator for measuring irregular areas shown in Figure 5, is an application of this principle. A plate uniformly covered with polonium is positioned far enough below a wire mesh grid so that only the most perpendicular alpha radiation can ionize the space between the grid and the top electrode. If a plane surface of unknown area is placed on the grid, the ionization current will be reduced by an amount proportional to this area. The grid mesh is connected to the lower plate. Use of a radioactive grid resistor of polonium keeps the plate current of the tube constant for equal surfaces in spite of the decay of polonium.

The radioactive arrangement of Figure 5 can also be used to measure porosity and open areas of mesh surfaces, integrate the values of curves or charts that have been cut out along their peripheries determine the most efficient layouts of patterns to be cut or stamped from metals or fabrics and measure areas of such things as precious metals foils furs and leathers. If the radioactive plate is coated with a beta emitter the apparatus can be used for thickness or density measurements of plastic

or organic materials and for volume determinations. For metallic materials the radioactive energizing material should be a gamma ray emitter.

DETECTING DISPLACEMENT

When radioactive material is coupled directly or indirectly to the moving part of a system, variations in position cause variations in ionization current or light effect that are readily amplified to give practically any degree of sensitivity and precision.^{6,7}

A typical application here is the radioactive galvanometer in which a vane appropriately plated with radioactive material

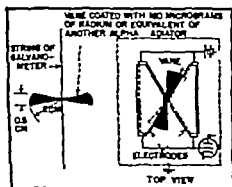


FIGURE 6 Radioactive galvanometer

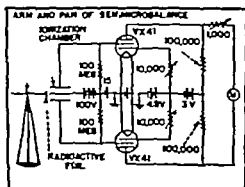


FIGURE - Radioactive balance.

is attached to the moving system in place of a mirror as indicated in Figure 6. With a simple one-tube amplifier a rotation of one minute here would lead to a change of between 10 and 40 microamperes in plate current for the vane dimensions

M. Blau and I. Fefer Method for Detection and Measurement—the Move-
ment of a Body. U. S. Patent 731380

¹M. Blau, Method and Apparatus for Indicating and Measuring Small Movements, U S Patent 2,443,344.

shown. With appropriate refinements the sensitivity can be even further improved.

The above technique is applicable to any type of torsion meter. The radioactive material on the moving part can alternatively cause emission of fluorescent light from a screen monitored by phototubes. Since ionization and phototube currents can both be easily amplified, the method lends itself nicely to remote reading or telemetering.

The movement of a balance can be magnified greatly by coupling to the balance arm a radioactive foil situated near a double ionization chamber as in Figure 7. With the arm length of an ordinary semimicrobalance, the radioactive adaptation was capable of recording variations of 1 microgram. The accuracy of a microbalance was thus combined with the ruggedness of a semimicrobalance. The radioactive balance has the further advantage of indicating directivity above or below an equilibrium position.

The radioactive balance arrangement shown in Figure 8 can be used for production weighing of small quantities of material within a predetermined accuracy.* The vertical positions of the ionization chambers can be adjusted so that maximum meter reading occurs when a predetermined weight of material is in one balance pan. The sharpness of the peak of the maximum reading can be adjusted by means of diaphragms at the openings of the ionization chambers to give the degree of accuracy desired. With high enough radioactive intensities or increased amplification in the output circuit it would be possible to energize a relay controlling a valve that would permit only a certain amount of material to flow onto the balance pan.

* M. Blau and I. Feuer, *Weighing Device and Weighing Method* (limiting balance). U. S. Patent Application 748636.

A radioactive arrangement suitable for leveling or for determining the degree of inclination is shown in Figure 9. Any deviation from a horizontal position of the beam increases the current in one phototube and simultaneously decreases it in

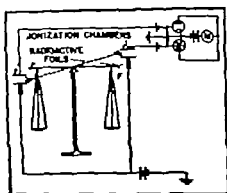


FIGURE 8 Radioactive limiting balance.

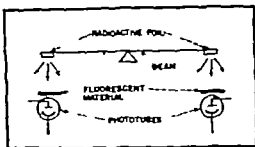


FIGURE 9 Radioactive leveling method

the other. If the outputs of the phototubes are arranged in a bridge circuit, the instrument can be made quite sensitive and can be adapted for automatic releveing.

The radioactive micrometer shown in Figure 10 is based on the fact that the range of alpha particles in air is about 1 000

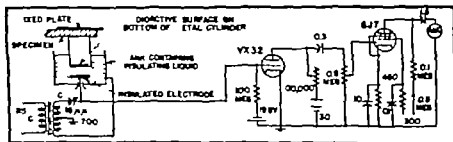


FIGURE 10 Radioactive micrometer arrangement and circuit.

times greater than their range in certain insulating organic liquids. Small variations in spacing between the plates of an ionization chamber situated in such a liquid give a consider

able percentage change in ionization current. The spacing is determined by the thickness of the specimen being measured. It is possible to measure the heat extension of materials within an error of $\pm 1 \times 10^{-6}$ inch. While the maximum change in length or thickness covered by this instrument depends upon the range of the radiation and the stopping power of the liquid, it is possible to measure greater changes by appropriate displacement of one of the electrodes.

To avoid polarization of the liquid, a-c voltages are applied to the ionization chamber. Capacitor C is used to nullify the alternating current that would flow through the capacitance of the ionization chamber to the grid of the first tube. The operating point of the first tube is chosen to minimize the ionization current that would flow during the inverse portions of the applied voltage.

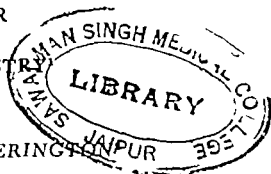
The devices discussed in this chapter are merely representative examples of the forerunners of a wide range of industrial applications. The number of these will increase immeasurably with the progress of the science of radioactivity and the increasing availability of its raw materials.

CHAPTER V

ATOMIC POWER

FOR INDUSTRY

BY H ETHERINGTON



NUCLEAR or atomic energy is developed in a reactor¹ in the form of heat. Some of the engineering problems of extracting and applying the heat usefully and economically will be indicated in this chapter

NUCLEAR ENGINEERING OF THE REACTOR

Calculation of a reactor requires a level of mathematics higher than commonly necessary for engineering design. Hith

¹ The material in this chapter is from an article in *Machine Design* July 1948 and is reprinted by permission.

² Mr. H. Etherington was formerly Director of the Power Pile Division at Oak Ridge National Laboratory and at present is Director of the Naval Reactor Division of Argonne National Laboratory. He has been on leave of absence from the Allis Chalmers Mfg. Co. since 1946 to assist in development of atomic power.

Reactor has been adopted by the Atomic Energy Commission as a preferred term for a "pile."

erto reactors have been calculated by theoretical physicists; but engineering progress in peacetime development of atomic energy demands that this work be transferred to the realm of engineering

The Fission Process Heavy nuclei tend to be unstable and under sufficient impetus may undergo fission, i.e. may break down into two smaller nuclei. After fission of a nucleus, the two parts remain positively charged and by mutual repulsion acquire a very high velocity (about one thirtieth of the velocity of light). The particles are stopped by surrounding solid or liquid matter in considerably less than 0.001 inch of travel, and the kinetic energy of the particles is converted into heat.

Critical Mass There is only one naturally occurring, readily fissionable material. This is U^{235} which is present in the amount of 0.7 per cent in natural uranium, the balance being almost entirely U^{238} . When fission occurs in U^{235} , in addition to the two major fragments, some surplus neutrons appear as debris from the disintegration. The neutrons are emitted at high speed, approximately one fifteenth of the speed of light, and nuclear engineering is concerned largely with the fate of these neutrons. On the average, one to three neutrons per fission are emitted. The actual number is, of course, known, but the information is secret and in order to make the ensuing discussion more concrete we shall assume that there are two neutrons released for each fission of U^{235} .

If the planetary system of a single atom be represented by a circle 12 inches in radius and a barely visible dot be made at the center with a hard pencil, this dot might represent to scale the size of the nucleus of the atom. A neutron is somewhat smaller still. An individual nucleus, therefore, presents an exceedingly small geometric target and neutrons can wander

through matter with considerable freedom so that many of them escape from a reactor and are lost completely. In a reactor containing only a few atoms of U^{235} the total effective target area presented by the U^{235} nuclei would be so small that if a fission occurred within the reactor most of the two neutrons would escape and no chain reaction could occur. If the U^{235} is increased until the total effective target area is such that there will be one fission hit for each fission occurring then a self-sustaining "chain reaction" will result and the weight of U^{235} is called the critical mass for the particular reactor.

Nuclear Fuels Although U^{235} is the only naturally occurring, easily fissionable material, both of the practically nonfissionable nuclei U^{238} and Th^{232} (thorium of atomic weight 232) can absorb one neutron per nucleus and after two subsequent spontaneous nuclear changes become the new easily fissionable nuclei Pu^{239} (plutonium of atomic weight 239) and U^{233} (uranium of atomic weight 233) respectively. Neither of these materials occurs naturally on earth. Of the two neutrons assumed to be obtained from fission of a U^{235} nucleus one is needed to continue the chain reaction and the other one is under ideal conditions available to convert a nucleus of U^{238} or thorium into a new fissionable atom. Industrial power reactors must be designed to secure advantageous use of this available neutron. In fact conversion is so important that the whole future of large-scale atomic energy may well depend on the degree of conversion attainable, the optimum condition being production of at least one new fissionable atom for each atom consumed in the reactor and so eventually to make available for fission the relatively large resources of thorium and U^{238} .

The presently known nuclear fuels are thus U^{235} , Pu^{239} and U^{233} . The first of these is present in natural uranium and can

be used without separation from the associated U^{238} . However, direct use of natural uranium does not permit good neutron economy and in general will require a considerably larger reactor and bigger critical mass than for the concentrated fuel.

Uranium enriched in U^{235} is being produced at the \$500,000,000 separation plant at Oak Ridge, and when military conditions permit ⁴ it is presumed that this material will become available as initial charge material for industrial plants. It is probable that such plants may then have to generate fuel for continued operation from the cheaper and more abundant materials natural uranium and thorium. Plutonium is being produced in the large Hanford plants and it is hoped that it will become available ultimately for use in the same way as U^{235} . The third fuel, U^{233} exists only in quantities sufficient for laboratory investigation and will not be commercially available until large scale reactor operations have permitted manufacture of this fuel.

Fast and Thermal Reactors If the fast neutrons from fission are permitted to bounce around in a mass of atoms at ordinary temperatures they will impart their excess kinetic energy to the atoms by collision and may ultimately be slowed from their initial velocity of about 12,000 miles per second to a velocity of about 1.4 miles per second, at which they will be in equilibrium with molecular and atomic movement at ordinary temperatures. A fast reactor is one in which the chain reaction is sustained by neutrons that retain much of their initial velocity whereas in a thermal reactor fission is produced by neutrons that have been slowed approximately to thermal velocities.

⁴ *Atomic Energy for Military Purposes*, by Henry D. Smyth, Princeton University Press. This is an official, semipopular report of the wartime development of atomic energy.

At thermal neutron velocities the effective target area of fissionable nuclei is increased several hundred times consequently the critical mass of fissionable material can be much smaller for a thermal reactor than for a reactor operating on fast neutrons. This decrease in inventory of a very expensive and scarce material strongly favors adoption of a thermal reactor for industrial purposes. Heat transfer considerations lead independently to the same selection.

The Moderator The material employed to slow the fast neutrons is called a moderator. Moderators must be chosen from among the elements of low atomic weight and their compounds. If atomic weight were the only criterion the most effective moderators would be hydrogen, heavy hydrogen, helium, lithium, beryllium, boron, carbon, etc. in the order named. However, other considerations eliminate helium, lithium, and boron, so we are left with hydrogen, heavy hydrogen, beryllium, and carbon, or their compounds, as the only promising moderators.

THE PROBLEMS OF DESIGNING THE FIRST POWER REACTOR

Figure 1 shows diagrammatically the basic features of a promising type of atomic power plant. The reactor is constructed of moderating material pierced by a large number of parallel holes. Fissionable material is inserted in the core or center part of the reactor. The core is surrounded by a reflector, probably of the same material as the core and of similar construction. This reflector is the breeding ground for manufacture of new fissionable material from thorium or from U^{238} placed in the holes of the reflector. Neutrons leaking from the core

into the reflector have their direction changed by collision with atoms of the reflector and many get turned around and re-enter the core, thus permitting a decrease in the critical mass. Other neutrons that would otherwise escape become absorbed in thorium or U^{238} and so promote neutron economy.

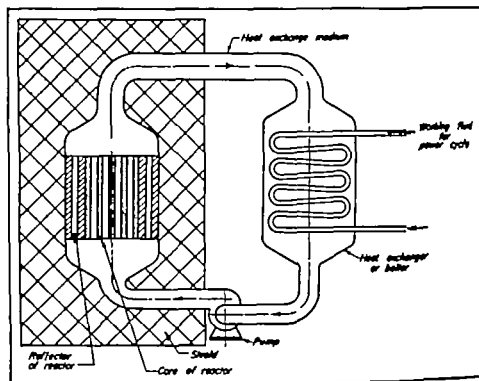


FIGURE 1 Schematic arrangement of an atomic power plant. The working fluid may be steam or gas for use in a conventional turbine or other form of engine.

Heat received by the recirculated coolant or heat exchange medium is transferred in a heat exchanger to the working fluid for the power cycle. The working fluid may be steam used in a conventional steam turbine plant, air or gas for use in a gas turbine cycle, or any other fluid that can suitably be used in any form of heat engine.

At the present time it is not possible to exclude any type of

reactor from consideration. There are many difficult selections to be made and it may be necessary to build several power reactors before the ultimate trend of industrial atomic power plant practice becomes clearly established.

The Kind of Reactor Much heat exchange surface and reactor bulk is necessary for extraction of the large quantity of heat to be developed in a power reactor. A thermal reactor already provides this bulk in the necessary moderator wherein it differs from a fast reactor. It has been explained moreover that a thermal reactor has a much lower critical mass of fissionable material than a fast reactor. The thermal reactor therefore offers a promising line of development for atomic power plants.

The natural uranium-graphite-moderated reactors built during the war are very large (Figures 2 and 3) and therefore provide the bulk favorable to high power output. However they are expensive to build and, as has been stated, natural uranium does not provide the good neutron economy desired for making new fissionable material.

Present indications therefore, appear to favor a thermal reactor operating on enriched U^{235} with subsequent substitution of U^{238} as the reactor breeds this fuel from thorium.

Choice of Materials for Use in Thermal Reactors In addition to the moderator the reactor may have to contain other constructional materials. The operating conditions in a power reactor severely restrict the choice of constructional materials. In varying degree the nuclei of all atoms absorb neutrons and except where this absorption results in fission or conversion of a nonfissionable nucleus to one that is fissionable, this represents a parasitic loss of neutrons.

Neutron economy prohibits extensive use of any of the common metals within the reactor. Some use of aluminum is per-

missible and minor parts of iron and the other common metals can be tolerated

Some elements such as boron have such an enormous affinity for neutrons that they can be tolerated only in traces and exceptional purity is demanded in all reactor materials which are used in considerable quantity

After preliminary selection of materials in accordance with nuclear requirements it becomes necessary to consider fabrication and procurement problems and to satisfy normal engineering requirements. Obviously the material must be sufficiently strong at the temperature of operation and must be chemically inert to the coolant and other materials in contact with it. The very high heat release in a relatively small volume of material makes it necessary to pay particular attention to material properties and designs conducive to low thermal stress

Application of materials to new fields has in many cases yielded unexpectedly disappointing results. In a reactor the conditions of service will be radically different from those in any tried and proved application and cautious exploratory work will be necessary before any material can be used with entire confidence.

Radioactivity When a nucleus absorbs a neutron or undergoes some other type of change, the nucleus commonly finds itself with surplus energy over its ground state—it is said to be in an excited state. The excess energy is usually dissipated by emission of one or more gamma rays, identical in character with very high-energy x rays

The nuclear changes occurring within the reactor give rise to unstable nuclei that, like radium, undergo radioactive decay extending over an indefinitely long time. Consequently not only is there intense radioactivity directly associated with neu

tron absorption while the reactor is in operation but there is also continuous emission of gamma rays at a gradually declining rate for some time, even after the reactor is shut down.

Nuclear reactions also give rise to alpha particles, which are essentially high velocity helium nuclei, and beta particles which are high-velocity electrons.

Shielding of reactors to protect personnel from the effects of radiation is of course of paramount importance. Shielding from alpha and beta rays is easy because these charged particles are stopped in a small fraction of an inch of travel in solid matter. Gamma rays and x rays must be reduced to a safe level by heavy shielding just as in industrial radiographic work. Slow neutrons may be absorbed in human tissue with production of gamma rays and fast neutrons may cause even more extensive damage when they impinge on atoms in the tissue. Such effects are taking place continually in the human body under the influence of cosmic rays and some increase in this normal condition is tolerable. Tolerance standards and methods of measurement have been established and the shielding design must assure that exposure will be well below the tolerance level which experience has shown to be safe.

The shielding must contain sufficient neutron absorbing elements it must contain light elements to slow down the fast neutrons so that they can be more readily absorbed, and it must absorb gamma rays which can be best accomplished by heavy elements but which can also be accomplished by a sufficient thickness of light elements. Ordinary concrete provides a cheap but bulky compromise of conflicting requirements. The word "cheap" is relative only since reactors may be large and the concrete must be several feet thick.

Heat Exchange Medium The more obvious heat exchange

mediums include air and other gases water and liquid metals. Liquids are inherently superior to gases in that they require less pumping power for a comparable rate of heat removal.

Water is excellent as a *coolant* and is used to cool the large plutonium producing reactors at Hanford, Washington (Figure 3). However water is far from ideal as a *heat exchange medium* for production of power because the system must be operated at extremely high pressure to produce heat at a thermodynamically desirable level. Use of water presents the additional problem of finding materials acceptable from a nuclear standpoint, that will resist corrosion at elevated temperatures and that will not develop films detrimental to heat transfer.

Choice of liquid heat exchange mediums other than water appears to be restricted to those low melting metals and alloys that have suitably low neutron-absorbing characteristics. Obviously the use of liquid metal at high temperatures will pose serious metallurgical problems.

Air is used as the coolant in the reactor (Figure 2) operated at Oak Ridge National Laboratory Tennessee, for production of radioisotopes and for experimental purposes. The heated air is discharged through a stack with no attempt at heat recovery. The reactor to be completed at Brookhaven National Laboratory Long Island will also be air cooled and heat will be recovered from the air to generate electric power as a by product. The temperature level will however be much lower than desirable for a true power reactor—at really high temperatures graphite would burn and aluminum metal parts if used in the reactor would oxidize.

Inert gas as a heat exchange medium may well solve the

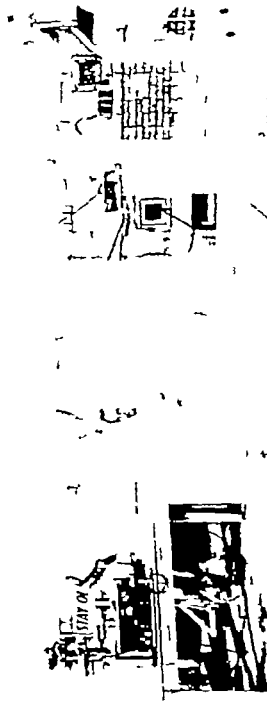
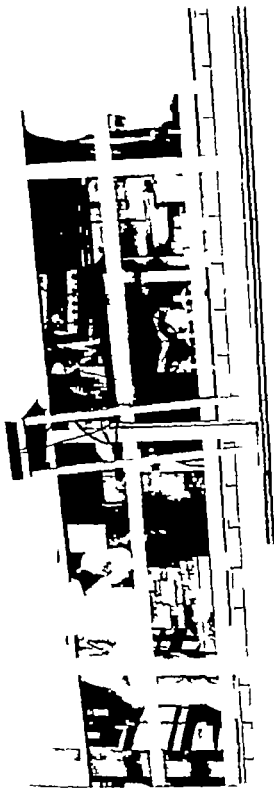


FIGURE 2 One
face of the Oil Ridge
test x This face
shows plugged holes
used for experimental
purposes. Personnel
protected by thick con-
crete radiation shield
(Photo by J. F. West
coll.)



r. 3 One of the
 on streets at the
 Engineer Work
 sec, Washington



Figure 4. Remote control and weaving equipment for small scale process work conducted inside a concrete cubicle



FIGURE 5 Process equipment viewed through one of the special periscopes shown in Figure 4

problems of chemical and metallurgical attack—in fact, helium was originally considered as the coolant for the Hanford reactors. However, to keep the pumping power within reason it will be necessary, as in the case of water, to operate the system under pressure. Gases alone appear to hold promise of attaining really high temperatures such as would be required for gas turbine plants or for high-temperature process work. It can only be said at this time that the choice of coolant is controversial.

Fuel Canning The uranium slugs used in the Oak Ridge and Hanford reactors are encased (canned) in aluminum jackets. The reason is twofold: (1) Uranium metal is highly active chemically and is oxidized by air and corroded by water; (2) The intensely radioactive fission products must not be permitted to enter and contaminate a coolant that is being continuously discharged. Development of adequate canning methods at Hanford was a very difficult problem because the container must be gas-tight and must permit uniform cooling of the uranium slug at all parts.

Even for a coolant flowing in closed circuit, canning is at least highly desirable. For high-temperature application it is necessary to solve the metallurgical and chemical problems of undesired alloying and diffusion, the fabrication problems of canning complex shapes required for good heat transfer, and the usual high-temperature operating problems of warpage and plastic deformation.

Chemical Problems During operation the uranium and thorium slugs undergo nuclear and physical changes which make it necessary to withdraw them periodically for chemical reprocessing and refabrication. The extraordinary radioactivity

fuel may prove to be a negligible item in the cost of atomic power

On the other hand, the investment costs of the power plant will be greatly increased by addition of the reactor. It has been estimated that a complete nuclear power plant employing a modified Hanford type of reactor would cost about two and one-half times as much as a coal power plant and that on this basis the nuclear plant would be competitive if coal costs \$10 per ton. However the Hanford reactor was considered in that study chiefly because design and operating data were available for this type of reactor. A reactor design primarily for power production may be expected to present a more favorable picture than a modification of a reactor designed for another purpose.

Probably nuclear power will find its first competitive application where transportation adds greatly to the cost of conventional fuels. Such applications include marine propulsion to increase the payload by eliminating bunker fuel and power installations in regions remote from fuel supplies.

Another promising application for nuclear energy is production of very high temperatures. The temperature attainable in a reactor is limited only by the refractoriness of the constructional materials used, so that it is possible to attain direct temperatures now requiring expensive electric heating. Technological difficulties suggest, however, that high temperature production must await successful development in the intermediate temperature range of the nuclear power plant.

How Soon Could a Nuclear Power Plant be Built? Men

* The International Control of Atomic Energy. The Department of State Information was prepared in the office of Bernard M. Baruch and transmitted to the United Nations Atomic Energy Commission.

tion has been made of the expected production of byproduct power from the Brookhaven National Laboratory reactor. This incidental production of power may not be a significant step in development of nuclear power and the reactor probably should not be considered as a power reactor in the accepted sense.

With the urgency that characterized the project during the war and with a small fraction of the wartime effort, there is little doubt that experimental high temperature power reactors could be built within two years to produce a few thousand kilowatts of electrical output, and that early development of large power reactors could be forced. In this country there appears to be no need for this degree of urgency. However, in other countries geographic and economic conditions may well point to a greater urgency, and it need hardly be pointed out that an extensively developed unpoliced atomic power industry presents an enormous military threat.

The expensive high-purity materials necessary in a reactor, the elaborate control system to insure safe operation, and the very extensive shielding to protect personnel against radiation all contribute to make a reactor an extremely expensive unit. The requirements are similar whether the reactor is developed for small or large power output, and even an experimental reactor with its appurtenances will cost several millions of dollars.

The effort and expenditure that can be allocated to a development and construction program for experimental atomic power plants at this time must be weighed against military demands and the demands for expanded experimental scientific work. These difficult decisions must be made by the

Atomic Energy Commission, and unofficial speculation concerning the rate of atomic energy development should be given little weight.

CONCLUSION

Continuing research is paving the way to successful development of an atomic power industry by expanding our knowledge of reactor characteristics by developing suitable materials and by contributing to the solution of many other problems. The engineering problems are neither trivial nor insuperable; they must be solved by engineering development proceeding concurrently with research. Components must, of course, be designed and tested, but experimental reactors must also be built and operated before commercial atomic power can become a reality. The engineering development probably will take many years and a concentrated major effort must not too long await further study of fundamental problems.

CHAPTER VI

CHEMICAL PROCESS CONTROL WITH RADIOACTIVITY¹

BY ALAN P SCHREIBER²

SINCE radioisotopes became available from Oak Ridge a little more than a year ago much publicity has been given to advances in fundamental research and in the field of medicine brought about through the use of radioisotopes. Little except vague generalities has been written about new developments which may be expected within the next few years from the application of radioisotopes and tracer techniques to industrial problems both in the plant and in the industrial research laboratory.

Such a situation is to be expected because, prior to the Manhattan Project few people had dreamed that we would ever have inexpensive radioactive materials of widely varying char-

¹Based on an article in *Chemical Engineering*, January 1948 copyright by McGraw Hill Publishing Company Inc.

²Mr Alan P Schreiber is at present employed by the Tracerlab Inc., Boston, Mass.

acteristics available in the relatively large quantities required for industrial purposes. Until last year the minute quantities of radioisotopes available from cyclotrons were of such a low order of magnitude that few workers in radioactivity conceived of their use in large-scale industrial processes where daily consumption might run in millicuries instead of a few microcuries as in typical prewar research.

However government regulations regarding the use of radioisotopes have not given industry full encouragement to begin development of industrial applications of radioactivity. Up to the present radioisotopes have been restricted to use in publishable research, either fundamental or applied, and for medical purposes. No provision has yet been made for permitting their utilization in any industrial process. Now however steps are being taken by the Atomic Energy Commission to improve this situation.

The chemical industry in particular has been built on a highly competitive basis and process secrets are numerous. Some manufacturers are reluctant to pursue research on potential industrial applications because of the requirement that results of such work be freely available to others. The patent situation on discoveries of patentable processes utilizing radioisotopes is not entirely clear regarding the right to exclusive use by the inventor or his assignee. Litigation proceedings of one or more test cases in a court of law will clarify this issue.

Questions arising from potential health hazards both to plant workers and to the consumer are further deterrents to activity in the industrial field. Despite the excellent safety record of the Manhattan Project, there still remains the unanswered question of the long term effects from continued exposure of per

sonnel to less than the currently accepted conception of tolerance radiation dosage.

There is the ever present threat of nuisance suits instigated by consumers against manufacturers who permit products to leave their plants containing small amounts of residual radioactivity. Keeping the radioactivity remaining in finished products at a level far below tolerance will not be difficult. Even minute amounts of radioactivity in consumer products may for a time, cause the manufacturer considerable embarrassment owing to consumer ignorance and to inadequate precedent in court rulings of damage suits involving low concentrations of radioactivity.

USES OF RADIOISOTOPES

Literally tens of thousands of potential industrial uses of radioisotopes exist. Virtually every industry can profitably utilize the properties of one or more of the hundred-odd radioisotopes whose half lives and availability permit their consideration for industry. At present there is need for serious and penetrating consideration of the potentialities of radioisotopes in industry. Active development is needed for those uses which can do a more efficient job than currently available methods in improving process control and quality, lowering processing costs by saving labor and material, or serving as a warning mechanism to protect personnel from health hazards inherent in a process.

To get some conception of the industrial usefulness of radioactivity, let us consider how the rayon industry might use radioactivity and tracer techniques. The rayon industry is

chosen not because it is particularly adaptable to these techniques. Rather, it is because uses adaptable to this industry are typical of those in many others such as rubber, plastics, fine chemicals, petroleum refining, and paper.

Before making an analysis of the rayon process, it should be understood that many of the uses of radioactivity which will be described have not yet been seriously investigated as commercial possibilities. The examples given are merely illustrative of what might be done rather than what has been done or what is contemplated in the immediate future.

The process is as follows. Cellulose, usually in the form of sulfite paper pulp, is treated with caustic to form alkali cellulose. Carbon disulfide is then reacted with the alkali cellulose to produce cellulose xanthate, a crumbly solid. The xanthate is formed into a solution of high viscosity by the addition of water and sodium hydroxide. This solution, called viscose, is forced under pressure through spinnerettes containing tiny holes into a coagulating bath to form yarn filaments. The filaments are then washed and passed through a desulfurizing bath to completely remove all residual sulfur. They are next coated with a lubricant such as sodium oleate, a polyvinyl alcohol, or a petroleum base oil.

If tracer quantities of radioactive sulfur³⁵ as carbon disulfide are added in the xanthating process, there are several uses to which it could be put in process control.

A part of the sulfur is removed in the coagulating bath and the rayon filament is completely freed of it in the desulfurizing bath. Continuous routine check of sulfur removal can be made by placing a Geiger Müller counter in close proximity to the rayon filament or the solutions through which it passes. Since the radioactive sulfur is a fixed proportion of total sulfur pres-

ent, the total amount of sulfur removed in the coagulating bath can be quickly determined. Also a check is easily made after the desulfurizing bath to determine whether complete removal of sulfur has resulted. It is quite possible that automatic electronic controls could be devised to keep the coagulating and desulfurizing baths within predetermined concentration ranges by coupling the output of the Geiger-Müller tubes through a suitable servomechanism to valves on chemical solution tanks

SAFETY DEVICES

A health hazard exists at several stages in the process. Hydrogen sulfide, carbon disulfide vapor and mercaptans all highly poisonous are liberated in the coagulating bath. The use of carbon disulfide tagged with sulfur³² can alleviate this hazard. Since the sulfur in both the hydrogen sulfide and in the mercaptans originates in the carbon disulfide, these compounds will also contain radiosulfur. Radioactivity monitoring devices placed in areas where leaks are likely to occur can be made to sound an alarm when sulfur containing gas or vapor escapes.

Such monitoring devices can be made sufficiently sensitive so that they will detect a leak before plant personnel will smell the odor of the escaping gas. Even more useful is a portable radioactivity detection instrument for locating the exact spot at which the leak is occurring. The low-energy beta radiation of sulfur³² makes it somewhat difficult and expensive to use for this purpose; however it can be made to operate successfully. An alarm system such as this should prove even more valuable in plants processing highly poisonous gases which do not have distinctive odors or which are cumulative poisons.

In preparing the viscose solution cellulose xanthate crumbs

are dissolved in sodium hydroxide to form a solution of a pre determined concentration. The dissolving and dilution process can be automatically controlled by use of radioactivity techniques. A patent has been granted (U S Patent 2304910) for determining specific gravity of fluids by measuring backscattering of radioactivity from the solution being measured.

SPECIFIC GRAVITY MEASUREMENT

Briefly this method is as follows. A collimated source of hard gamma radiation is placed outside of the container hold-

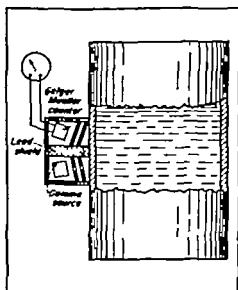


FIGURE 1 Specific gravity is measured by a Geiger Muller counter that detects backscattering of gamma rays

ing the liquid for which the specific gravity is desired. The radiations impinge at an acute angle on the container wall. A Geiger Müller counter coupled to a counting rate meter is mounted to receive scattered radiation from the gamma source.

A lead shield is placed between the counter and the source of radiation absorbing virtually all radiation from the radioactive source which is emanating in the direction of the Geiger Müller counter. Figure 1 shows a diagrammatical representation of the apparatus.

A substantial portion of the rays enter through the container wall into the solution. The rays are scattered within the fluid in the container and the amount of scattering per unit volume depends upon the density and composition of the fluid. Considerable scattering will result as the rays pass through the container wall but, knowing the density and thickness of the wall, a constant correction factor can be applied. A portion of the scattered rays are reflected back to the Geiger-Müller counter the counting rate detected being a function of the intensity of the gamma source and the density and thickness of the materials upon which the rays have impinged. For a given system the counting rate meter can be calibrated to read directly in specific gravity. It is claimed this device has been used with a high degree of reproducibility in measuring fluid densities between 0.7 and 1.0 gram per cubic centimeter in a pipe 6 inches outside diameter with wall thickness of 0.3 inch.

An instrument such as this can be easily coupled to valves automatically controlling the amount of caustic and water to be used in dissolving a batch of cellulose xanthate to form a solution of predetermined specific gravity.

If desired a higher degree of accuracy can be attained without the necessity of shielding the Geiger Müller counter by placing the source of gamma activity within the tank and measuring the amount of radioactivity detected by a Geiger Müller tube placed outside the container.

The backscattering phenomenon has many useful applica-

tions For example, using a similar instrument to that shown schematically in Figure 1 piping and tanks can be inspected for internal corrosion without draining or interfering with the process in any way If the density of the liquid in a pipe and the material from which the pipe is made are known then it is not at all difficult to calibrate the counting rate meter in terms of pipe wall thickness

This instrument integrates pipe wall thickness over an area of roughly 1 square inch and will measure thickness to within about 5 per cent. Such equipment is now made commercially and is particularly valuable in industrial processes where corrosion problems are serious It does have the limitations of being insensitive to deep pitting and scale corrosion where corrosion products adhere to the metal.

LIQUID LEVEL GAGE

A liquid level gage utilizing radioactivity has recently been developed which can be used to indicate liquid level in any tank used in the manufacture of rayon This gage is particularly useful where highly corrosive liquids are to be measured or where it is desired that the tank have no openings through which gas or vapor can leak A float containing a hard gamma emitter which is constrained to vertical movement, is placed inside the tank A Geiger Müller counter coupled to a counting rate meter calibrated in liquid depth is mounted directly above the float and outside of the tank.

As the distance between the radioactive float and the Geiger Müller counter changes there is a corresponding change in the detected counting rate which is indicated on the calibrated meter The output of the Geiger Muller counter can be utilized

to open a filling valve when the liquid falls below a predetermined level. Figure 2 shows a diagrammatical representation of this equipment.

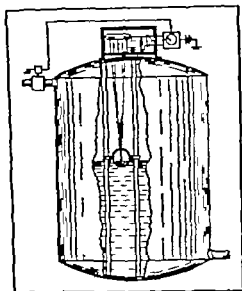


FIGURE 2 Liquid level instrument uses a counting rate meter and a graded float containing a gamma ray emitter

Dyeing process control is for the most part, an art rather than a science because so many independent variables are present. Radioactivity can be of considerable assistance in controlling two of these variables namely the dye concentration in the dye bath and the weight of dye absorbed by the fabric. The continuous dyeing process in which fabric is passed through a dye vat in a continuous length is particularly adaptable to this type of control. If one or more radioactive atoms were incorporated into the dye molecule and tracer quantities of it were mixed with the normal dye, the concentration of dye present in either the cloth or the dye vat could be continuously and automatically determined by Geiger-Müller counters. Elec

tronically actuated controls can regulate the dye bath concentration in such a way that the weight of dye per unit area of cloth emerging from the dye bath will be a predetermined constant. Process controls such as these will eliminate substantial variations in shade between the beginning and the end of a dyeing run which sometimes result with presently used methods

TRACING REACTIONS

The mechanism by which free sulfur appears in the coagulating bath and in the yarn is not fully understood. Sodium sulfate is added in the xanthate dissolving process to retard the appearance of coagulable cellulose. It is not known whether the sodium sulfite produces more sulfur in the yarn than does the carbon disulfide which reacts to form the xanthate. Tracer amounts of sulfur³⁵ incorporated into either carbon disulfide or sodium sulfite molecules can follow the course of sulfur from either source.

The presence of small amounts of manganese, iron, copper chromium and certain other metallic ions in the viscose solution have resulted in production of rayon filaments of inferior characteristics. These materials accelerate the aging and ripening process and if properly controlled they might be advantageously utilized to shorten the time required for aging and ripening. Radioisotopes could be used in studies to determine the lower limit of metallic ion concentration which affects the aging and ripening rate since this lower limit may well be below that detectable by conventional chemical methods.

In all industrial applications of radioactivity considerable care must be exercised in choosing the proper level of radio-

activity concentration and the proper radioisotopes to use for eliminating the health hazards of excessive radiation exposure of plant personnel. Every effort should be made to utilize isotopes of fairly short half lives and with as low an energy level as is consistent with desired sensitivity of the process control instrumentation. In locations where the radiation is unshielded from plant personnel, it is quite important that only alpha or beta emitters be used unless gamma emitters in low concentration can be satisfactorily utilized.

PROBLEMS INVOLVED

A further point of importance in considering industrial applications of radioactivity is the amount of activity remaining in the finished product. Most of the uses described in this chapter provide for removal of the radioactive material during the process. In the few instances where this is not the case, radioisotopes of short half life should be used in sufficiently low concentrations as to constitute no health hazard to the ultimate user. Thus it is evident that the extent to which radioactivity can be used in processes where it is not removed from the finished product is limited by the number of radioisotopes that have both the requisite chemical properties and a short half life.

At least 88 elements have one or more radioisotopes available from natural sources, from pile irradiation, or from cyclotron bombardment that have half lives sufficiently long to be considered for use in industrial processes. Lack of diversity of radio elements is little cause for concern.

It is unlikely that radioactivity will cause widespread revolutionary changes in the process industries within the next sev-

eral years. Inertia, lack of personnel trained in the field of radioactivity and a general tendency of waiting for someone else to take the first step will all contribute to slow initial development. Furthermore, the advantages gained in utilizing tracer techniques are frequently out of proportion to the required capital outlay.

Undoubtedly radioactivity will very shortly be called upon to solve many problems which have seriously troubled industry for some time and for which no satisfactory solution has been found in any other method. These will be the first and probably the more spectacular applications. After that, imagination, economics and ingenuity will determine the future course of radioactivity in industry.

CHAPTER VII

RADIOACTIVE TRACERS

IN METALLURGICAL RESEARCH¹

BY E S KOPECKI²

With most of its senior staff participating, the Carnegie Institute of Technology Metals Research Laboratory has been engaged in a broad integrated fundamental research program designed to add to the knowledge of the basic science of metallurgy. Operating as a participating unit of an overall Office of Naval Research program, the Carnegie program has been and is concerned primarily with the rates and mechanisms of metallurgical reactions in molten metals and in solid metals.

In the section on liquid metals, efforts have been directed mainly toward a study of reactions in steelmaking and particularly the measurement of activities of constituents in liquid metals and slags and the mechanism of reaction across a slag.

¹ By permission from *The Iron Age*, an article appearing in its issue of September 4, 1941, has been used for this chapter.

² Metallurgical Editor of *The Iron Age*.

metal interface. The work of the solid metals section has been primarily concerned with the rates of diffusion and concepts of interatomic forces and activities in solid solutions which may be inferred from diffusion data

Tracers have been used in seeking the sulfur transfer coefficients and the calcium deoxidation constant in experiments on the reactions across the slag metal interface, in the work on the self-diffusion of iron in studies of the mechanism of scaling of iron and in efforts to examine microsegregation. It is planned to use them even more extensively in further research.

The overall Carnegie project is spread over several lanes of research embracing the fields of physical and process metallurgy with both of these fields broken down to numerous subdivisions.

The section on physical chemistry of steelmaking is directing part of its efforts toward a study of mechanisms and kinetics of slag-metal interface reactions in an attempt to determine the rates and mechanisms whereby elements which are soluble in both slag and metal cross the interface between the two phases. Sulfur and oxygen are two such elements which are of fundamental importance to steelmaking; consequently they were singled out as the first to be studied.

A good start has been made at determining rate constants for sulfur transfer from slag to metal and from metal to slag, but a finished research in this phase of the program is not expected until the mechanism of the transfer of sulfur across a slag metal interface has been worked out with the aid of radioactive sulfur. When these experiments have been concluded it is expected that the work will be extended to the problem of oxygen transfer utilizing vacuum fusion apparatus.

and the melting and sampling techniques developed for the sulfur study

With radioactive calcium already in the laboratory work is under way for determining the solubility of calcium in liquid iron and the calcium-oxygen equilibrium in iron. This is an excellent illustration of the application of radioactive tracers to a research problem which cannot be solved in any other way. Classical methods of chemical and spectrographic analysis are not sensitive enough to detect any solubility of calcium in steel but extremely low concentrations of calcium may be detected if some of the calcium atoms are radioactive. Radioactive calcium will, of course, behave chemically the same as ordinary calcium and the radioactivity will not be altered by high temperatures.

A slag is made up from radioactive calcium carbonate together with ordinary silica and alumina. Working in a ventilated hood see Figure 1 this slag is placed over liquid iron saturated with carbon in a graphite crucible. It is expected that a trace of calcium may be reduced from the slag and enter the metal. The amount of calcium can be determined by suitable calculations from the rate of radioactive disintegration as measured by a Geiger Muller counter. Figure 2 shows the scalers and the lead chamber that houses the Geiger counter and sample being counted.

Several experimental difficulties remain to be solved before any results can be reported. Experiments are being made under reducing (blast furnace type) slags and the effect of changes in slag basicity is being investigated. This portion of the program is based on the assumption that the solubility of calcium in iron will be great enough to be detectable by radioactive counting methods. Should the activity be too low to measure,

it is expected that the negative result will still be of scientific importance, since it will enable some estimate to be made of the maximum solubility of calcium in iron

In the work of the molecular constitution of slags a study of ionic properties is being conducted to help elucidate the constitution and properties of slags. In attacking this phase of the program, use is made of electromotive force measurements, ionic mobility studies, and conductivity studies. In the past, the Carnegie staff developed a carbon-silicon carbide couple which provided a measure of SiO_2 activity in the slag; consequently the laboratory expects some success in further studies being conducted along these lines.

As a first step in investigating the nature and mobility of ions in liquid slags and metals experiments have been set up to determine whether an impressed electrical field across a slag-metal interface will alter the distribution of sulfur between slag and metal. It is proposed to continue studies of this sort, extending the work to the distribution of oxygen between slag and metal on the one hand and the mobility of ions within the slag phase only on the other hand.

Also scheduled for the near future is the direct determination of the activities of various elements in liquid slags and metals by vapor pressure measurements, using radioactive tracers where available, to facilitate analysis. The method will involve condensation on a cold target of an atomic beam streaming through a pinhole orifice in a crucible containing the liquid slag or metal at high temperature, the entire operation being conducted under high vacuum. In cases where the vapor pressures become too high for application of the atomic beam technique, the saturation or "dew point" method, such as used for vapor pressures of zinc in brasses can be employed. Slow

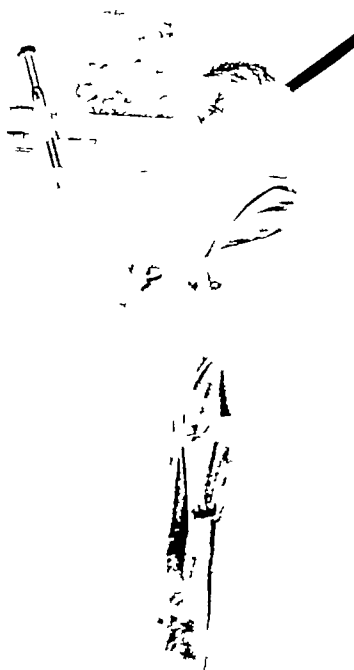


Figure 1 Check
radioactivity with
Geiger Muller counter
in hood used for melt
experiments with
radioactive tracers
(All photos in this
report by Charles
Nelson)



FIGURE 2 Counting radioactivity in samples for metallurgical research



FIGURE 3 Apparatus for controlling atmosphere and temperature for diffusion specimens.



FIGURE 4 - Lik rowing on a gas barge

delivery of certain parts of the intricate apparatus for the atomic beam method has delayed these experiments until now

In the physical metallurgy section which is working on diffusion of metals the diffusion measurements under way or anticipated were selected for one of five purposes (1) To provide data for the analysis of the kinetics of the austenite pearlite reaction, (2) to substantiate the theoretical studies on binary diffusion recently made on this project* (3) to extend present ideas on diffusion into ternary systems (4) to amplify existing information in systems of interest to the metallurgist which display properties which are not entirely metallic and (5) to study diffusion in structurally analogous systems as a basis of correlation of diffusion with other physical factors. Some of the diffusion apparatus is illustrated in Figure 3

In the work of the kinetics of the austenite-pearlite reaction fundamental diffusion data being sought are the rate of self diffusion of iron in both the alpha and gamma ranges and the rates of diffusion of carbon in gamma iron. At the present time the experimental determination of self-diffusion in both alpha and gamma iron using radioactive iron as a tracer is almost complete. It is planned, in this phase of the program to continue work on theoretical studies on the mechanism of austenite decomposition.

The section dealing with the theory of binary diffusion in solid metals plans to study the gold-silver system to seek confirmation of a theory developed on the project.² It is believed that the diffusion coefficient is invariant with composition if activities rather than concentrations are used in the diffusion equation and a critical test of this theory would be best pro-

* C. E. Birchenall and R. F. Mehl, *Thermodynamic Activities and Diffusion in Metallic Solid Solutions* *Metals Technology* 14 June, 1947 T P 2168 (AIME)

vided by a system of two completely miscible metals which can be obtained in very pure form and which are not susceptible to oxidation. Hence, the desire for work with the silver-gold alloys.

In delving into the theory of diffusion in ternary alloys, plans have been made to work on a representative of each of three possible types of systems in which (1) all elements are substitutional, (2) one constituent is interstitial, and (3) two components are interstitial. The Cu-Ni-Zn system is an attractive example of the substitutional type of alloy because data already exist for diffusion in the binary systems, but difficulties in preparation of the alloys (zinc boils at 980 °F below the melting point of nickel) may force selection of some other system. The Fe-Si-C system will be explored as representative of the second type of alloy and it is expected that Fe-C-B will provide the example with two interstitial components.

Because of the extraordinarily strong and mysterious influence of boron on the hardenability of steel, a preliminary determination of the effect of boron on the diffusion of carbon in alpha iron is already in progress. The Fe-C-B system also falls within the scope of other research and the projects will be coordinated to supplement one another in such a way as to study this very interesting system without duplication of effort.

In fact, the full scope of the laboratory's research on metallic diffusion can best be appreciated, not from this project alone, but from the coordinated program which embraces work under several sponsored projects and doctorate theses. Most of this work, which is in progress or scheduled to start, is outlined as follows:

A) Diffusion of iron (using radioactive iron)

- 1) Rate of self-diffusion of iron in alpha and gamma iron

- 2) Effect of carbon concentration on self-diffusion of iron
 - 3) Rate of surface self-diffusion of iron
 - 4) Rate of diffusion of iron in every dilute solution in copper nickel, and cobalt.
- B) Diffusion of other elements in iron
- 1) Effect of carbon concentration on the rate of diffusion of carbon in gamma iron
 - 2) Determination of rate of diffusion of hydrogen nitrogen and boron in alpha iron Effect of these elements on diffusion of carbon in alpha iron and effect of carbon on the diffusion of these elements in alpha iron.
 - 3) Determination of rate of diffusion of hydrogen and boron in gamma iron The effect of these elements on diffusion of carbon in gamma iron and effect of carbon on the diffusion of these elements in gamma iron
 - 4) Determination of the rate of diffusion of chromium and silicon in alpha and gamma iron the effect of carbon on the rate of diffusion of these elements in alpha and gamma iron and the effect of chromium and silicon on the diffusion of carbon in alpha and gamma iron
- C) Studies on the mechanism of diffusion in binary metallic solid solutions
- 1) The influence of lattice vacancies on diffusion using nickel aluminum and cobalt aluminum alloys in which the number of vacancies may be controlled
 - 2) Precise study of interface movement in metallic diffusion the "Kirkendall Effect," and quantitative de

termination of countercurrent flow in diffusion, especially in the brass system

- 3) Nature of the grain boundary and its importance in diffusion penetration of bismuth into the grain boundaries of solid copper as related to the relative orientations of adjacent copper crystals and other variables
 - 4) Optical (reflectivity) study of surface diffusion in the silver-copper system.
 - 5) Interdiffusion and self-diffusion of gold and silver in gold-silver alloys and correlation with activities.
 - 6) Other theoretical studies on the mechanism of solid diffusion based on re-evaluation of published and unpublished data already available.
- D) Studies on diffusion in ternary nonferrous systems, copper nickel zinc or copper nickel-tin.

The use of radioactive tracers at the Carnegie laboratory has made it possible for the staff to study diffusion mechanisms in oxide films and thereby to investigate the processes of the scaling of metals. In working with iron, for example, a very thin layer of radioactive iron is electroplated on a polished surface of pure iron. The metal is then oxidized under controlled atmosphere and temperature, and the scale formed is stripped off in very thin layers by acid etching. The distribution of radioactive iron through the scale yields information as to whether the scale builds up by diffusion of oxygen to the iron or of iron to the oxygen.

It has already been found that the mechanism of oxidation is more complex than earlier investigators had suspected. The work has been expanded to include scaling under conditions to

produce all the possible combinations of single and multiple iron oxide layers. Figure 4 shows part of the apparatus used to produce controlled atmospheres for selective oxidation. It is planned to extend this work to the scaling of other metals where tracers are available.

Supplementing the work in diffusion will be a determination of the activity of zinc in alpha and beta silver zinc alloys by vapor pressure measurements. Since diffusion data are expected to become available for this system, it will then be possible to correlate diffusion with activities and to relate activities to short-range ordering to verify conclusions drawn earlier in the project from the structurally analogous brass system.⁴ Direct evidence on short range ordering should be obtained by x-ray methods for the silver zinc system, whereas copper and zinc atoms have too nearly the same scattering power to make this independent certification of ordering possible for the brasses.

The study of the mechanism of reactions in the solid state is hampered by the absence of techniques for determining concentration gradients on a submicroscopic scale. For example, the decomposition of austenite to form pearlite would be better understood if one could know the carbon concentration gradients in the austenite immediately ahead of the advancing front of pearlite, and across the newly formed lamellas. High carbon steels containing radioactive carbon have been prepared by carburizing pure iron using BaCO_3 containing radioactive carbon as the energizer. Efforts are being made to develop "autoradiomicrographic" techniques with the use of extremely finegrained photographic plates. At the moment, it appears

C. E. Burchenall, "Interaction and Structure in Copper Zinc Alloys," *Metals Technology*, 14, June, 1947, T.P. 2169 (AIME).

that the resolution obtainable will not be great enough to be useful in the study of the microscopically fine details of austenite decomposition products

Handling of radioactive materials used in the project, naturally presents a potential health hazard, and requires that suitable safeguards be enforced. Fortunately, there is comparatively little danger involved in intelligent handling of the tracers used in this metallurgical research because of the small quantities used and the low level of activity of the samples. In fact it has proved to be a greater problem to devise means of counting low energy beta rays than to provide proper protection of personnel from radiation.

Health regulations provide for periodic blood counts, medical examination if indicated, and rotation of personnel where necessary to minimize the cumulative effect of irradiation. The rules specify the minimum requirement for checking hands, body, clothing and working areas for radioactive contamination together with maximum permissible limits for such counts. All counts and exposure meter readings must be recorded. It is also necessary to include instructions for decontamination or disposal of contaminated articles or wastes, to outline first aid for injuries, to place restrictions on eating places, and to caution regarding smoking habits to avoid inadvertent ingestion of radioactive materials.

Although the Carnegie program is intensive and organized into specific channels of research as outlined above, flexibility is being maintained so that emphasis can be shifted to allow for unexpected results in the experiments and concurrent developments in the metallurgical research field at large.

It is believed by the research staff that the information obtainable from this program will help in providing a sound basis

for the re-evaluation of steel making reactions. And, with the thought in mind that rates of diffusion have been very little explored the staff is aiming at exploitation of this field of science so that this one of the controlling factors in reactions in the solid state may be better understood and utilized.

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by the heat released there. The reactor therefore replaces the boiler of a conventional power plant. The steam expands through the turbine, which drives the propeller. The steam is then condensed in an air-cooled condenser and is forced back into the boiler-reactor by a feed pump. This type of power plant

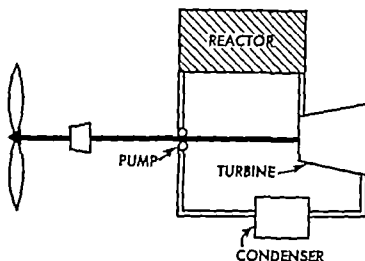


FIGURE 1 Closed cycle turbine.

requires the use of both a propeller and an air-cooled condenser which will evidently limit the airplane speed at which it can be used. For that reason it does not appear as practical as other possible applications.

Another application of atomic energy is in the turbo-jet. What is done here is simply to remove the combustion chamber of the conventional turbo-jet and replace it with a nuclear reactor. Air is compressed and forced through the reactor where it is heated by convection instead of by combustion of fuel. It then expands partially in the turbine, enough to provide sufficient power to drive the compressor and finally in the jet nozzle where it creates propulsive thrust. This type of power plant is very well suited to high-speed airplanes.

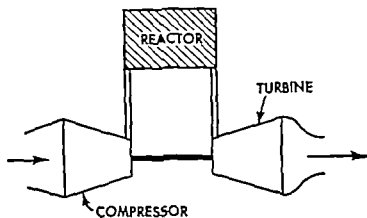


FIGURE Turbo-jet.

On paper the ram jet is the simplest type of power plant conceivable. Air enters the diffuser at the front end of the engine and is compressed by the forward speed of the plane. It then passes through the nuclear reactor where it is heated to a high temperature, and goes into the exhaust nozzle, where it expands and acquires a high velocity to provide thrust. The ram jet requires a high flight speed to function at all and be

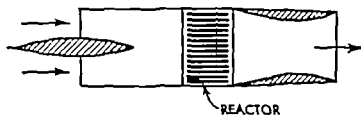


FIGURE 3 Ram jet

comes really effective at extreme speeds high in the supersonic region. The air temperatures required by the ram jet are very high, considerably higher than those needed by the turbo-jet. At the same time, the ram jet is very sensitive to pressure drops caused by the internal flow resistance of the reactor or combustion chamber. Good heat transfer conditions must always

be paid for by appreciable pressure drops. The ram jet is therefore not quite the simple problem it appears to be at first glance.

In the application of nuclear energy to a rocket a propellant (liquid hydrogen for example) is pumped out of the tank and through the reactor where it is vaporized and heated to a high temperature. It then escapes at high velocity through the exhaust nozzle. The rocket is driven by the recoil of the escaping

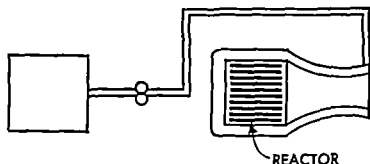


FIGURE 4. Rocket.

propellant and thus is not dependent on atmospheric air for its functioning. It can therefore, operate outside the earth's atmosphere.

One may well ask where the advantage lies in using nuclear energy for rockets since their endurance is limited and they can operate only until the fuel is exhausted, regardless of the practically unlimited supply of energy in the reactor. Nuclear energy offers a definite advantage in rockets because the maximum impulse, the pounds of thrust that can be obtained from each pound of fuel used per second results from a combination of the highest possible temperature and the lowest possible molecular weight of the fuel.

The high temperature is obtained normally in a chemical rocket by the combustion of a fuel and an oxidizer whose products of combustion are then used as the propellant. Since the

propellant is the result of the combination of at least two atoms its molecular weight will be fairly high. If hydrogen and oxygen are used, the resulting propellant is water vapor with a molecular weight of 18. If nuclear energy is used to provide the higher temperature, there is no need for the process of combustion and a very light propellant, like hydrogen with a molecular weight of 2, can be used. The specific impulse of pure hydrogen at the same temperature is three times that of water vapor.

Many of the problems which lie in the path of the practical realization of atomic aircraft power plants are connected with the use of high temperatures. Unlike chemically fueled engines high thermal efficiency is not the primary reason for wanting high temperatures in a nuclear engine. Specific fuel consumption is of vital importance in a chemically fueled engine. However, for a fuel with a heating value of 40 billion Btu per pound (like uranium) specific fuel consumption is vanishingly small, from a performance standpoint, and thermal efficiency in itself is not a primary objective. High performance is however and high performance calls for high operating temperatures. For instance, a high thrust per pound of airflow per second is required in turbo-jets for high-speed airplanes. This requires a high energy input for each pound of air and, therefore, a high air temperature.

The temperature problem is aggravated by the heat-transfer problem. We actually are taking a long step backwards along the road of development in the lightweight engine. The great advance in lightweight design which made the automobile and airplane possible, came to pass when it was learned how to avoid transferring heat through walls as in a boiler. In other words with the advent of internal combustion

In a nuclear engine, the heat is generated in the solid portions of the reactor and must be transferred to the working fluid through heat-transfer surfaces. Fortunately we have learned a lot about heat transfer in the past fifty years so we are not starting quite as far back as the gasoline engine.

One basic fact remains, and that is that the internal surfaces of the reactor must be at a temperature higher than the highest temperature of the working fluid since heat must flow from the reactor into the fluid. It can flow only if there is a positive temperature difference. This is very different from the internal combustion engine where, as in the automobile, the cycle temperatures reach 4,000 degrees while the internal surface temperatures can be kept down to around 500 degrees by external cooling. On the other hand there are no moving parts in the reactor and the reactor elements are not subjected to the high dynamic stresses which are encountered in such parts as pistons, valves or turbine buckets. It can be said broadly that the temperatures necessary for the realization of an atomic engine are not unreasonable from the metallurgical standpoint, but they do nevertheless engender a number of difficult problems.

One of these problems is the protection of the uranium in the reactor against corrosion by the working fluid and, conversely the prevention of the escape of the radioactive fission products from the reactor into the working fluid. This is a problem of diffusion and diffusion rates generally go up with increasing temperature. The development of adequate canning for the high-temperature reactor elements is therefore, a major problem.

Another crucial problem as in any aircraft, is weight. In an atomic engine, it is necessary to use large amounts of mass to

stop radiations emitted during the fission process. A comparison with a conventional airplane can help us visualize the magnitude of the weights which may be allotted to shielding. The weight of the propulsion system comprises substantially three major items: the power plant proper, the fuel, and the fuel tanks. In the nuclear aircraft, these correspond to the engine (compressor-turbine assembly in a turbo-jet), the nuclear reactor, and the shielding.

The "engine" component of the nuclear installation may be expected to weigh approximately the same as a conventional power plant of the same horsepower or thrust rating. The weight of reactor and shielding is therefore equivalent to the weight of the fuel and fuel tanks in a chemically fueled aircraft.

The percentage of the airplane gross weight which can be allotted to fuel and fuel tanks, or to reactor and shielding, depends primarily on the structural refinement of the airplane. In present-day long range airplanes, it represents a very high percentage of the gross weight and is in some cases well in excess of 50 tons. It is therefore obvious that the problem of an atomic-powered airplane is in an entirely different category from the problem of an atomic powered automobile, although they have often been mentioned together in discussions of atomic energy.

Not only the absolute weight of the shielded reactor is important, but also its specific weight, or its weight per unit of thrust produced by the power plant. The weight of the shielded reactor is tied in with the gross weight of the airplane by structural efficiency. The aerodynamic efficiency of the plane, the ratio of lift to drag, ties in the required power plant thrust with the airplane gross weight. The required lift is equal to the gross weight, while the resultant drag must be overcome by the power

plant thrust. By combining these relationships, we arrive at a formula which ties in the power plant performance with the aerodynamic and structural characteristics of the airplane. The specific weight of the reactor must be less than or equal to, the lift-to-drag ratio times the ratio of permissible reactor weight to airplane gross weight. The range of an atomic powered airplane is practically unlimited and is not a design variable.

Shielding weight is influenced about equally by two entirely separate variables. One is the size of the reactor core around which the shielding must be wrapped. The other is the thickness of the shielding itself or, more precisely, the mass thickness needed to stop gamma rays and neutrons emitted by the fission process.

Making the reactor small is an obvious way of reducing weight of shielding. However, it means releasing energy at a high rate in a small volume. Although a nuclear reactor can potentially generate heat at a practically unlimited rate, this heat must be conducted from the interior of the fuel rod to its surface. It must then be transferred from the surface to the working fluid, meaning high temperature differentials, high pressure drops, large internal surface areas and all other difficulties associated with high power densities. Furthermore, the smaller a reactor is, the larger the ratio of its surface area to its volume and the easier it is for neutrons to escape without causing new fissions. A smaller reactor may therefore require a larger investment of uranium in order to sustain the chain reaction and this may prove undesirable from an economic standpoint.

As far as mass thickness of the shield is concerned, the best materials for stopping a given type of radiation of a given energy are relatively well known. However, the radiations emitted by

a nuclear reactor are of two major types neutrons and gamma rays each covering a wide spectrum of energies. As they pass through the shield, these radiations gradually change their character. The fast neutrons slow down by successive collisions with nuclei of the shield material the gamma rays are absorbed and in turn softer x rays are emitted. A material which is good for stopping gamma rays may not be the best when gamma rays and neutrons are considered together and a material which is good for the innermost part of the shield may not be best for the outer layers. There is therefore, considerable room for weight reduction by ingenious design.

Since we are dealing with a relatively thick shield surrounding a relatively small reactor the apparent paradox holds true that, for a given mass thickness the greater the density of the shielding material the lighter the shield. If the density of the shielding material is doubled and the thickness of the shield is cut in half the volume of the shield is decreased by considerably more than a factor of two and the total weight is reduced accordingly.

From the point of view of conventional power plant experience, shielding may be used as a good example of some of the unusual aspects of nuclear engineering. If 2 inches of lead reduce some radiations to one tenth their original intensity, 4 inches of lead will reduce them to one hundredth, and 6 inches to one-thousandth of the original intensity. The radiation intensities encountered in nuclear reactors must be reduced by factors of many billions before they are safe for humans.

A good reflector may turn back as many as 90 per cent of the neutrons escaping from the reactor but it would be wrong to assume that this would solve nine-tenths of the neutron shield

ing problem. It is more likely to represent only about 10 per cent of the job. In addition, it is very important to prevent the escape of seemingly small amounts of radiation through joints or seals in the shield around the reactor.

The choice of materials for shielding also presents unusual problems. Existing reactors mostly use large quantities of concrete for shielding, but concrete is hardly a suitable aircraft material. The effect of intense radiation on the properties of the materials must also be considered. It has been found that the electrical resistance, the elasticity and the heat conductivity of graphite all change with exposure to intense neutron radiation.

The atomic-powered airplane must be designed for very high speeds to take advantage of the special characteristics of atomic power. It certainly will be a large airplane. It will have to be designed for a landing weight which is equal to takeoff weight, since practically no fuel will be used up in flight. Because of radiation, the crew locations should be placed as far away from the power plant as possible. That would permit some weight saving in the shield.

Structural requirements will be somewhat different from those of conventional airplanes since the fuel load will be concentrated in one spot in the reactor rather than widely distributed. In this respect the atomic airplane may not differ much from some of the thin-winged, high-speed airplanes now under development which do not use wing tanks.

These are some of the problems associated with the development of a nuclear aircraft power plant. They are not insurmountable problems, but such a development is by no means an easy one.

CHAPTER IX

CERAMICS

AND NUCLEONICS¹

BY A. L. JOHNSON²

INTRODUCTION

THE impact of nucleonics on ceramics, the oldest industry now serving mankind,³ has been enormous, as has been its impact on every other industry. Changes in our thinking, new ideas and trends for research are the factors which ceramists must consider as a result of the experience attending the development of the atom bomb. The part played by ceramics in the development of this bomb, as carried out by the War Depart-

¹ Material in this chapter appeared in the *Bulletin of the American Ceramic Society*, 7 (6) June 15, 1948, and is used here by permission.

² A. L. Johnson, Sc.D., is director of research for the Universal Rundle Corp. For eight years he served on the MIT teaching staff. During the war he was with the Radiation Laboratory (MIT) and the Manhattan Project. Dr. Johnson during 1946-48 was on the staff of Iowa State College and also served as ceramic consultant to the Ames Laboratory (Atomic Energy Commission).

The ceramic industry can trace its lineage to the Neolithic Man of the Stone Age.

ment, Corps of Engineers (DSM project of the Manhattan District) although small, was vital

MANHATTAN PROJECT

In 1943, when the Metallurgical Laboratory⁴ had as one of its objectives the development of processes for the extraction preparation and purification of fissionable materials the need for extraordinary refractory containers was foreseen. Whatever process the immediate future would uncover for the preparation of these materials there would be a demand for refractories of unique specifications. Just as in the production of metallic iron from its ores where refractory materials have important functions, they would also be important in the metallurgy of fissionable materials. Extremely rigid specifications were placed in this instance on the refractory after a preliminary consideration of several factors. For example, slagging tendencies were to be avoided between the refractory and the metals upon whose recovery depended the entire experiment.

In this connection it may be worth while to recount the importance of the purity requirement of the ceramic materials. An account of the problems associated with the harnessing of atomic energy⁵ has stressed the importance to the success of the project of a value known as the "multiplication factor k ." This factor is the ratio of the number of neutrons produced by fission to the number originally present in the system. If the ratio falls below unity atomic fission obviously is not self sus-

⁴ The Metallurgical Laboratory was that part of the DSM project headed by A. H. Compton with headquarters at the University of Chicago.

⁵ H. D. Smyth, *General Account of Development of Methods of Using Atomic Energy for Military Purposes under Auspices of the U. S. Government*, Princeton University Press, 1945.

taining and will peter out. On the other hand, if the ratio is maintained at slightly greater than unity a self sustaining atomic chain reaction can occur. The success of the entire experiment depended on the multiplication factor. Since it was impossible to obtain a value based on anything other than actual test, the first uranium pile was built to determine, among other things, the value of k . Every human precaution was exercised to construct a pile according to rigid purity requirements since the presence of neutron absorbers within the pile could reduce the k factor.

Because many elements are neutron absorbers and the presence of such absorbers is detrimental to the operation of the device wherein the chain reaction proceeds the list of elements from which refractory shapes could be fabricated was quite limited. For example, it was believed that, because of impurities clay (the mineral kaolinite) could not be utilized in the development of refractories for this project. Special oxides and several other special refractory materials whose purity could be more easily controlled and whose compositions were such that neutron absorbing elements were absent were the object of study for use instead of the normal ceramic materials. This was the general overall picture early in 1943 about the time of the establishment of a ceramic group whose function would be to serve the metallurgical laboratory.

Ceramic problems, however, were studied at various stations before this time. For example, in the metallurgy of uranium Spedding⁶ and his group at Iowa State College had to overcome serious refractory problems before uranium of high purity could be produced. Rigid specifications on the metal were placed as

⁶ "Iowa State College Engages in Atomic Bomb Project," *Chemical Engineering News* 23 [22] 2076 (1945)

a result of the experimentally determined k factor previously mentioned. The details of these problems and methods for solving them are still closely guarded secrets. Certain ceramic materials were made at Iowa State to be used in the separation of isotopes by the cyclotron.

Similar experiences undoubtedly existed at the several research centers where work in connection with the DSM project was carried out. An interesting development resulted from work done at the University of California.¹ To answer their needs, refractory pieces were made out of cerium and thorium sulfides which had unique properties.

A ceramic group was functioning in the Metallurgical Laboratory in 1943, but because of the increasing number of problems which had to be solved, the group soon outgrew its facilities. In February 1944, the ceramic staff moved to new headquarters at the Massachusetts Institute of Technology.

The ceramic work at M I T dealt with three classes of refractories in an effort to cover every possible type which might be required by the entire DSM project. These included (a) oxides of thorium, beryllium, and magnesium; (b) various nitrides; and (c) sulfides of cerium and thorium.

The ceramic industry has utilized various oxides as special refractories from time to time. Whereas nitrides and their properties had been investigated by others, many of these compounds were extensively studied and refractory containers fabricated and tested for the first time because of work done on this project by various groups. The group at Iowa State investigated nitrides for certain uses before the ceramic group at M I T began large-scale investigations. As was previously mentioned, the group at Berkeley originally worked with the sul-

¹ E. D. Eastman directed the work of this group at the University of California.

fides which offered a great deal of promise. Calculations indicated that certain sulfides would display great stability *in vacuo*. In spite of the problems associated with the production and use of the sulfides their unique properties make them interesting ceramic materials.

Since no one knew definitely which type of refractory would best serve certain needs of the project, interest in one or another of the groups would fluctuate according to the results of tests which attempted to simulate the action of fissionable materials in an effort to predict their behavior. The simulated tests did not always give data which were reliable in judging the behavior of enriched fissionable materials.

It was impossible, therefore, to determine in advance definitely which type of refractory material would be required in the final operations.

For this reason each refractory material was studied thoroughly because of the possibility that it might be selected for use after final tests were made. This meant that sources of raw materials had to be developed to handle anticipated needs. In the cases of the nitrides and sulfides the problem of synthesizing a raw material of sufficient purity to meet requirements and in quantities which were considerably larger than laboratory methods could produce had to be considered. Consequently methods of synthesis in many cases had to be expanded to pilot plant size.

The fabrication of shapes was one of the most difficult problems with which the ceramist had to contend. Take away clay and its ability to be readily molded and those familiar with clay will have some idea of the difficulties encountered in the fabrication of intricate shapes from the nonplastic materials described. Casting techniques seemed to lend themselves read

ily when thin-walled items of symmetrical design were required, but these shapes were in the minority and the bulk of the shapes had to be produced by other methods. For reasons of purity, the ordinary types of binders could not be used in the pressing method of fabrication. New pressing techniques had to be developed so that ware could be produced. The problem of firing fabricated shapes was no small item. Although the ceramist is familiar with high temperatures and furnaces for the attainment of these temperatures such work is usually restricted to laboratory scale. In many cases temperatures from 1700 to 2400° C were required for production work. Furthermore, full-scale production firing in vacuums of 10^{-6} milli meter of Hg at temperatures of 1800° to 2100° C had to be undertaken with the work on sulfides and nitrides.

That these and other difficulties were successfully met is historical fact. It now behooves us to profit by the experiences of this undertaking. What are some of the factors which should influence the thinking of ceramists everywhere as a result of the studies on this project? It is a time to take stock and set forth new plans. This is the impact of nucleonics on ceramics!

RESEARCH TRENDS

As the scene is viewed from a distance, one fact is in better focus than all the others. Excluding the field of glass where new compositions have been developed, the white-ware field has been slow to develop new products. The traditional bodies (clay, flint, and feldspar) have been altered, but essentially the composition is similar to what was in use many years ago. Probably the principal reason for this is that clay is essential in the forming operation. Without clay this operation becomes so

difficult that soon all thought of new compositions disappears and the ceramist is back to the same triaxial composition once more.

If the ceramic industry is to supply ceramic materials for metallurgy of priceless fissionable materials which will result from studies in nucleonics if the heat-resistant members of jet engines or rockets are to be constructed of ceramic materials if ceramic materials are to be used as the specialized dielectrics required for radar or other types of communication circuits or to contribute in other ways to the development of a variety of new industries those upon whose shoulders rests the future of the industry must plan now for the proper developments which will permit ceramics to keep pace with its neighboring industries

In a recent report on the ceramic industry of Germany Russell⁶ discusses some interesting observations. For instance, alumina spark plugs are almost universally used in Germany. In fact, the fabrication of heat-resistant articles from various special oxides was generally farther along there than in this country. The methods of fabrication are important contributing factors. In this country the tendency is toward the so-called binder plasticizer or lubricant technique in an effort to overcome the difficulties of fabricating items containing no clay—the German industry however has utilized proper sizing techniques prepressing, or methods which do not impair the purity of the products. It is not that we lack the imagination. Given the opportunity, methods developed in this country by our scientists compare favorably with methods in use elsewhere. For example, the plastic flow of certain crystals at elevated tem-

Ralston Russell, Jr., "Electrical and Technical Ceramic Industry of Germany," Office of Military Govt. for Germany (U. S.) Fiat Final Report, No. 61-141 pp (1945) Ceramic Abstracts October 1946 p 133

peratures has been studied by Buerger⁹ with encouraging results. By virtue of this property a method of fabricating certain so-called nonplastic materials has been developed which overcomes many of the difficulties of the binder or lubricant techniques.

Instead of spending a major portion of the research effort on binders it would be well to devote some time to other approaches such as the one already mentioned.¹⁰ Another approach is based on a study of the rheological properties of nonplastic materials as a function of surface area in an effort to develop or enhance the property of plasticity in these special materials. This viewpoint has been discussed by the author previously¹⁰ and it received study during the war years in connection with important projects including the DSM project. It is the approach to be pursued at the Atomic Research Institute of Iowa State College in cooperation with the Department of Ceramic Engineering of that institution. The study serves a dual purpose in that it may increase ceramic knowledge and give information on the behavior of nonmetallic materials in general.

CONCLUSIONS

Instead of relying upon the old ceramic compositions of clay, flint, and feldspar for every need the ceramic industries are called by the nucleonic age to develop new compositions, techniques, and methods for use in the peacetime application of all the knowledge gleaned during the war. To keep pace with

⁹ M. J. Buerger, "Articles of Nonmetallic Compounds and Method of Producing Same," U. S. Patent 2362430 November 7, 1944.

¹⁰ E. A. Hamer and A. L. Johnson, "Plasticity of Clays," *Journal of the American Ceramic Society* 25 [9] 223-27 (1942).

the chemical, electrical, and aeronautical industries ceramics must take advantage of the experiences of the war years. Some of the information indicated herein has been restricted for reasons of security; it is being released, however, as rapidly as is consistent with good policy. This information should be carefully studied for proper utilization.

RADIOACTIVE MATERIALS

IN SOIL FERTILIZER RESEARCH¹

BY F W PARKER²

SCIENCE has given us an unusually powerful research tool. It will be used more and more extensively and will bring about changes in fertilizer production and use.

In this nontechnical discussion we will try to make clear the utility and limitations of radioactive materials in soil and fertilizer research. Our ideas will certainly change as we gain experience in this field.

The fertilizer industry is concerned with two distinctly different uses of radioactive materials. The first relates to the possible use of radioactive materials in fertilizers to influence crop growth. The second relates to the use of radioactive phos-

¹ Material in this chapter appeared in Vol. II, No. 2 of the *Plant Food Journal of the American Plant Food Council Inc.* and is used by permission.

² F W Parker is Assistant Chief of the Bureau of Plant Industry Soils and Agricultural Engineering of the U S Department of Agriculture, Beltsville, Maryland.

phorus sulfur and other plant nutrient elements in soil fertilizer research Both phases of the subject will be discussed

INFLUENCE OF RADIOACTIVE MATERIALS ON PLANT GROWTH

Soon after the discovery of radioactivity and radium the question arose as to their effect on the growth of plants Numerous experiments were conducted from 1900 to 1920 and in subsequent years Most of the work was carried out in Europe The U S Department of Agriculture and the Illinois Agricultural Experiment Station published bulletins on the use of radioactive materials as fertilizer in 1914 and 1915 respectively

The fact that some levels of radiation were harmful was soon established Evidence of a beneficial effect on growth was less conclusive Consequently the experiments did not lead to the commercial development of radioactive fertilizers, although there were unsuccessful attempts to do so

In 1937 Sir John Russell, Director of the Rothamsted Experiment Station reviewed the evidence and stated his conclusions in part as follows

"Some degree of stimulation of various processes has been claimed from time to time, but no clearly proved increase in plant growth has yet been obtained"

In 1944-47 a number of experiments were conducted by various agencies in cooperation with the Canadian Radium and Uranium Corporation A summary of the data shows a preponderance of positive results although the differences were not always large enough to be considered significant. The ex

* *Soil Conditions and Plant Growth*, 7th Edition, p 129

periments were not designed to eliminate the possible effects of minor elements and magnesium contained in the radioactive material under test.

It became clear that the public interest would be served if qualified scientists made a thorough study of the influence of radioactive materials on plants when applied to the soil. It was evident the experiments should include a wide range of crops and soils and several rates of radioactive materials. It also seemed essential to design the experiments so that relatively small differences could be measured. The Atomic Energy Commission made a grant to the Bureau of Plant Industry Soils and Agricultural Engineering to help support such a project. Plans for the work were developed in cooperation with a number of state agricultural experiment stations.

The uniform field experiment that was adopted includes three levels or rates of radioactivity and a comparison of radioactive materials. All treatments are replicated ten times in each experiment. Experiments are in progress today. They include nineteen crops and are located in fourteen states representative of the diverse soils and growing conditions in the United States.

In addition to the field experiments arrangements have been made for work in solution cultures in the greenhouse. Other experiments will study the effect of radioactive materials on seed germination and the early development of the seedling.

RADIOACTIVE TRACER TECHNIQUE

The reactions and properties of radioactive elements like radio-phosphorus differ from ordinary elements in only one respect. They give off a radiation as they disintegrate at a rate that is characteristic of the element. Ordinary phosphorus does



FIGURE 1 Weighing of radioactive phosphorus. This material is extremely dangerous to handle unless correct precautions are taken for convenience in handling it is transferred to bottles such as the one in the tongs. The bottles are stored in the lead storage chest. Note the precautions taken by the scientist when handling the hot material the long handled tongs, the lead shield in front of the table, the heavy rubber gloves, the mask, the film badge pinned on his pocket (Figures 1, 2, 3 and 4 photos by W. J. Mead.)

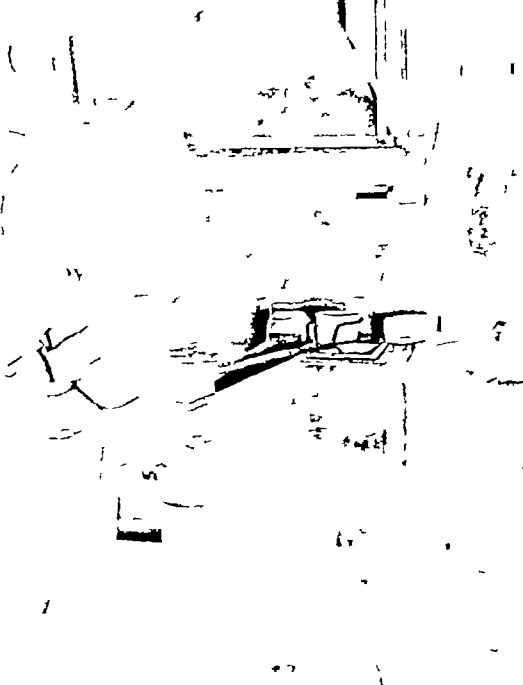


FIGURE 4 Production of radioactive calcium metaphosphate. The tracer technique offers an unusual opportunity to test the availability to plants of different phosphate fertilizers. The operator takes a crucible full of molten radioactive calcium metaphosphate from the furnace to the radiation meter held at his shoulder. This device is used in all operations to check on the level of activity at the working position.

not do this. This radioactivity makes it possible to detect or trace the radio-element wherever it may go in the soil, through the plant and in the animal. Thus we could fertilize a soil with radio-superphosphate, grow clover, feed the clover to a cow, and feed a calf on the cow's milk. After being on such a diet for a month, the calf's bones could be analyzed for total and radio-phosphorus. From the data we could calculate the amount of phosphorus in the calf's bones that came from the superphosphate. This general method is frequently called the "tracer technique" and is in general use in many fields of research.

The utility of the tracer technique depends in large measure upon the facility with which very small quantities of the radio-element can be accurately measured. The extremely small quantities measured may be illustrated by data on the preparation and use of radio-phosphorus in field experiments. Radio-phosphates produced at Beltsville, Maryland, contained approximately 125 pounds of phosphonic acid. Of that quantity only 1.4 pounds came from Oak Ridge. Less than one millionth part of the phosphorus received from Oak Ridge was radio-phosphorus P^{32} . The balance was ordinary phosphorus. We, therefore, had less than 5 milligrams of P^{32} in the 125 pounds of phosphonic acid. The 600 pounds of phosphate have been applied to about two acres of experimental plots. The fertilized plants will absorb less than one tenth of the applied phosphate. Yet the radio-phosphorus can be accurately determined in 1 gram of the plant tissue at the end of the growing season. By that time 99.9 per cent of the original radio-phosphate has decomposed. We measure what remains.

Before considering the results obtained with this technique in soil-fertilizer investigations, we will indicate the possibility of using it with different plant nutrient elements. There are

radioactive isotopes of all elements. The characteristics of some radio-elements however are such that they are of little or no value for our purposes. Table 1 gives the important characteristics and indicates the utility of the radio-elements of greatest interest in soil-fertilizer research. From this we see the following elements can be used in much the same manner as we are using radio-phosphorus, namely, sulfur, calcium manganese, zinc, iron and chlorine.

TABLE 1
Radioactive Isotopes of Some Plant Food Elements

Element	Isotope	Half Life	Utility
Phosphorus	P 32	14.3 days	One season
Potassium	K 42	12.4 hours	One week
Nitrogen	N 13	9.9 min.	One hour
Calcium	Ca 45	180 days	Years
Magnesium	Mg 27	10.2 min.	Hours
Sulfur	S 35	87.1 days	Years
Sodium	Na 22	3.0 years	Years
	Na 24	14.8 hours	Week
Chlorine	Cl 36	1 000 000 years	Millenniums
Manganese	Mn 54	310 days	Decades
Iron	Fe 59	44.0 days	Year
	Fe 55	4 years	Decades
Zinc	Zn 65	250 days	Years
Boron	B 12	0.022 sec.	Seconds
Carbon	C 14	5 100 years	Millenniums

It may be noted that with radio-calcium and sulfur as well as phosphorus, we have the necessary tools to evaluate fully the utilization of superphosphate by crops. We are inclined to forget that normal superphosphate contains about 25 per cent calcium oxide (CaO) and 30 per cent sulfur trioxide (SO₃) as well as 20 per cent phosphoric acid (P₂O₅). Both calcium

and sulfur are just as essential for plant growth as phosphorus. Yet today we know relatively little about the extent to which calcium and sulfur in superphosphate are utilized by crops. The tracer technique can provide the answer.

Radio-calcium will be very useful in liming experiments. Its long life makes it possible to use it in experiments of five years duration. Such work has been started at Cornell and some of the results will be discussed in a later section of this chapter.

Unfortunately the life of radio-potassium, magnesium, and boron is so short that they are of limited value. Radio-chlorine might be used in studies on its influence on tobacco, potatoes, and other crops where it is known to affect crop quality.

RESULTS OF EXPERIMENTS

The results obtained in this field of research will be illustrated for the most part from experiments with radio-phosphorus. The rapid progress in radio-phosphorus investigations has been possible because of the fine cooperation of capable scientists in several research agencies. The fertilizer industry has made important contributions toward this work through the Phosphate Research Committee.

Use of Fertilizer by Different Crops The 1947 field experiments in North Carolina and Maine revealed unexpected differences in the utilization of fertilizer phosphorus by different crops. Typical data are shown in Figure 5. In this case, corn, cotton, and tobacco were grown on the same soil. The fertilizer contained 80 pounds of phosphoric acid and was placed in bands. At the first sampling date, 65 per cent of the phosphorus in corn and tobacco was from the fertilizer as compared to 45 per cent in cotton. At maturity, the third sampling, only 15

per cent of the phosphorus in corn was from the fertilizer as compared to 35 and 45 per cent for cotton and tobacco, respectively

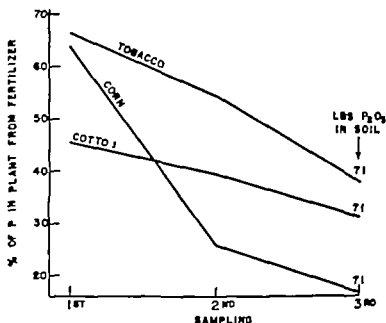


FIGURE 5 Use of fertilizer phosphorus by different crops.

The significance of these differences is not clear. It may be that some other placement of the fertilizer would improve the utilization of phosphate by corn. On the other hand, the data may indicate that corn can utilize soil phosphorus better than the other crops.

In following up the observed differences between crops, experiments have been designed to give many such comparisons on different soils. The experiments conducted in Colorado, Iowa, New York, North Carolina and Georgia include twelve different crops as compared to four in 1947.

Soil Fertility Influences Crops Use of Fertilizer The influence of the fertility of the soil on the utilization of fertilizer

phosphorus by cotton is shown in Figure 6. The crop was grown on three soils that contained 71, 140, and 216 pounds of readily available phosphorus. Differences in the utilization of the fertilizer phosphorus were evident at each date of sampling. At the final sampling the cotton grown on the least fertile soil derived 30 per cent of its phosphorus from the fer

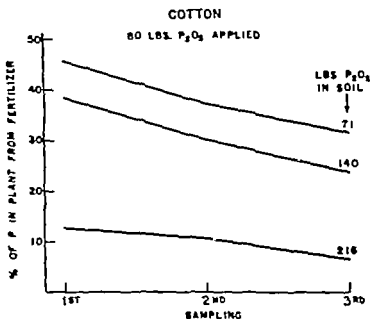


FIGURE 6 Soil fertility influences use of fertilizer phosphorus by cotton

tilizer. On the most fertile soil, only 7 per cent of the phosphorus in the crop came from the fertilizer.

The indicated differences are obviously important and have a direct bearing on fertilizer practices. It is far too early to speculate what effect new data of this character may have on fertilizer practice. We must first check our findings and obtain similar data for a variety of crops on different soils. Future experiments will afford such comparisons for about ten crops.

The soil conditions will vary widely and will include soils representative of the eastern midwestern and western states

The principle illustrated in Figure 6, namely that the phosphorus fertility of the soil influences the utilization of fertilizer phosphate, is being utilized in a short biological test for available soil phosphorus. It is essentially a modification of the well known Neubauer test. Early results indicate it will improve the utility of the test and at the same time simplify it materially.

Availability of Phosphorus in Green Manures A good green manure crop may contain 30 or 50 pounds of phosphoric acid in roots and tops. How good a source of phosphorus is this for a succeeding crop? Is it as good as an equal amount of phosphorus applied as fertilizer? Until we had radio-phosphorus, that could not be determined. Such determinations have been made in preliminary greenhouse experiments at Beltsville, Maryland.

Wheat fertilized with radio-phosphorus was grown as a green manure crop. The wheat was analyzed and mixed with soil at a rate to give 65 pounds of phosphoric acid per acre. In similar cultures an equal amount of phosphoric acid was applied as radio-superphosphate. All cultures were then planted to rye grass. Two successive cuttings of rye grass have been harvested and analyzed. The recovery of applied phosphate demonstrated that the green manure phosphate was nearly as efficient as superphosphate on each of the three soils used in the experiment. This was a higher efficiency than was expected.

Such results naturally lead us to consider several practical applications of such data. We must, however, take such experiments to the field and grow row crops after the green manure. The important point to remember today is that we

now have the tools to conduct such an experiment. As previously indicated, work need not be limited to phosphorus

Rate of Fertilization The influence of the rate of phosphate fertilization on the uptake of fertilizer phosphorus by the plant was shown in 1947 field experiments. Two rates of fertilization were used for corn, cotton, tobacco, and potatoes.

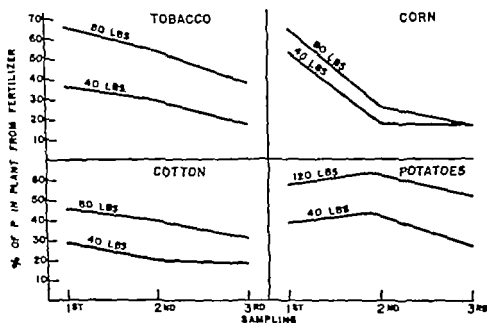


FIGURE 7 Rate of fertilization influences use of fertilizer phosphorus

The results of these experiments are shown in Figure 7. Increasing the rate of phosphate fertilization substantially increased the proportion of fertilizer phosphorus in the cotton, tobacco, and potatoes at each of the three sampling dates. There was only a small increase in the case of corn. The reason for this is not known. The experiment must be repeated.

The season's field experiments include rate of fertilization studies on six crops. The comparison will be made on several

soils that differ in their content of available reaction, and capacity to fix phosphorus.

Fertilizer Placement Only limited—very few experiments were devoted to the study of placement Fertilizer placement machinery was used to handle radio-fertilizers Facilities were also provided for the production of several hundred pounds of radio-phosphate made possible rather extensive phosphate experiments that are now in progress They include experiments with different crops The most extensive tests have been made with tobacco, and corn We are hopeful that the results will show how we can increase the utilization of phosphate by that important crop.

Efficiency of Different Phosphates. R²²²,
excellent tool for use in studying the relative
ferent phosphate fertilizers. We plan to use it
that purpose. To this end, facilities have been
the production in radioactive form of most
moderate or prospective interest to the farmer in
industry. Experiments in 1955 included com-
phosphate, a common salted superphosphate, double
phosphate, and calcium phosphate, and calcium phosphate
studies will be made on several crops and
at different levels of fertilizer

[illegible]



8 Fertilizer bags in corn field being loaded on truck. The bags are loaded on the belt of the fertilizer truck. Scientist has radiation hazard meter to detect radioactive material and out through

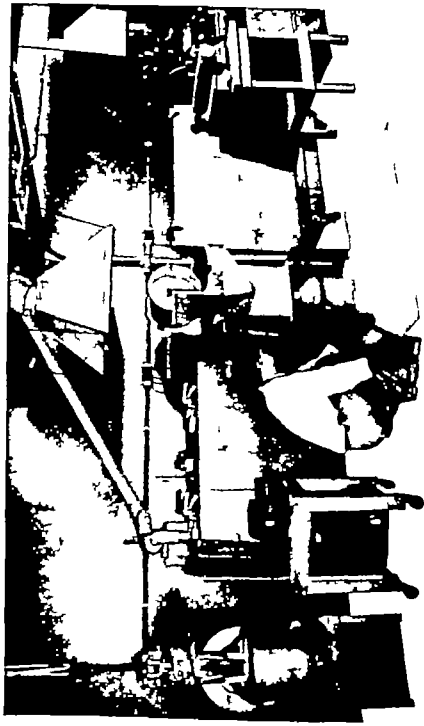


FIGURE 9 Production of radioactive superphosphate. A view of the laboratory showing all the equipment used for the preparation of radioactive superphosphate. This view shows the accelerator at far left the movable table with the lead shield, the drier the disintegrator, the ammoniator for producing ammoniated superphosphate, and a mixer on the right side of the post. The can of radioactive superphosphate being removed from the disintegrator will be emptied into the mixer. The material is mixed sampled, and analyzed before it is sent to the field for use in tracer experiments.

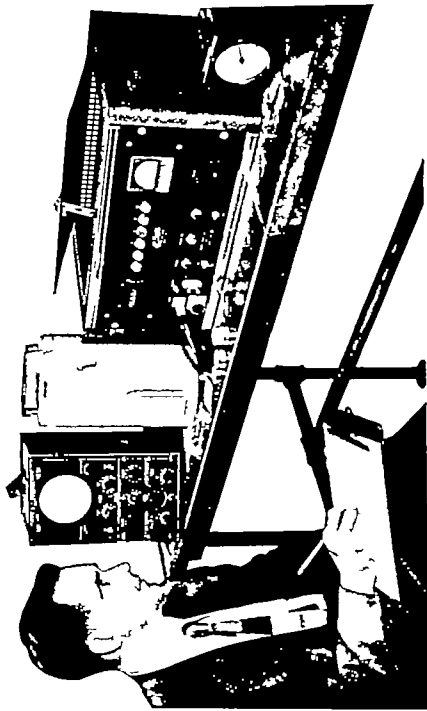


FIGURE 10 Measuring radioactivity in plant material

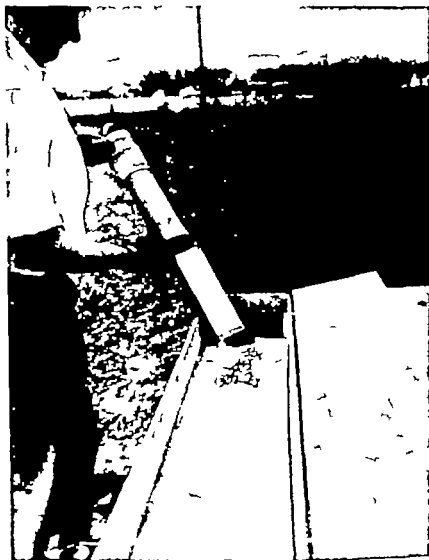


FIGURE 11 Placing radioactive superphosphate in the fertilizer distributor

may well demonstrate that they differ materially. If that should prove to be true, it could have quite an influence on fertilizers and fertilizer practice. It might complicate the formulation of fertilizers as well as increase their efficiency for the farmer. Forms or sources of phosphorus may be more important than sources of nitrogen. These statements are admittedly speculative. We will know a little more about this after the crops are in and analyzed. Several years however may be required to develop the data needed to guide fertilizer practice.

Measurement of Surface Phosphate The readily available phosphorus in soils is held on the surface of the soil particles chiefly on the clay fraction. There are three things we would like to know about this. First, how much phosphorus in a soil is held on the surface? Second, how tightly is it held? Third, how much phosphate could it hold? We have been able to answer the last question. Radio-phosphorus has made it possible to answer the first and second questions.

Using recently developed methods the surface phosphate has been determined on several soils. The quantity varied from 10 pounds P_2O_5 per acre in a Davidson clay loam to 180 pounds per acre in a highly fertile Caribou silt loam used for potato production in Aroostook County, Maine. The significance of this recent work is that the method is not empirical. It has been devised to measure the fraction of soil phosphorus readily available to plants. The method is believed to be applicable to both acid and calcareous soils.

Experiments with Radio-Calcium Workers at Cornell have utilized precipitated radio-calcium carbonate in greenhouse experiments in much the same manner as radio-superphosphate has been used. A silt loam having a reaction of pH 4.8 was limed at rates of 2,000, 4,000 and 8,000 pounds per acre.

Three cuttings of alfalfa have been made and analyzed for total and radio-calcium. In the first cutting the proportion of calcium derived from the added carbonate increased from 48 per cent where 2 000 pounds were added to 80 per cent where 8,000 pounds were added. The corresponding figures in the third cutting were 46 and 72 per cent. The need for lime and its utilization is clearly evident when the crop derives 70 per cent of its calcium from the added carbonate.

The long life of radio-calcium increases the hazards associated with field experiments involving its use. Our first field experiment with radio-calcium is therefore, being planned to study this problem. Scientists of the Atomic Energy Commission will cooperate in evaluating health hazards and developing procedures to minimize such hazards.

Progress achieved in training men and developing methods and techniques for using radio-elements in soil fertilizer investigations has been greater and in some respects more important than the actual results of the preliminary experiments. We have covered enough of the subject to show the utility and importance of this new tool in soil-fertilizer research. It will certainly be extensively used and have considerable effect on fertilizer practices.

CHAPTER XI

THE USES OF TRACERS IN BIOLOGY¹

BY G C BUTLER²

THE use of isotopes not commonly found in nature in high concentrations as tracers in biological research is based on the assumption that although these isotopes have different physical properties by which they can be detected and measured readily in small amounts they nevertheless behave chemically and biologically in a manner identical with their corresponding "normal" isotopes. This is a point which is not completely settled by any means but most biologists accept the premise with only slight reservations. However a few years ago it caused a great deal of controversy indeed especially when the use of this new tool in biological research began to yield results

Material used in this chapter appeared in the *Proceedings of the Conference on Nuclear Chemistry*, McMaster University, Hamilton, Ontario, Canada, 1947 and is used by permission.

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which were in conflict with some of the older theories. Much evidence was brought to bear on the problem and it soon became clear that as long as one administered only small tracer amounts of "heavy" or radioactive isotopes they would behave in the body similarly to other isotopes of the same element.

This statement has, however, two important qualifications. It holds only for conditions in the body where equilibrium has been reached, in the case of deuterium. Bonhoeffer was able to show that it reacted at a rate differing from that of hydrogen by a factor of six. So where there is a large mass ratio between isotopes they may lead one into error if used in studying the kinetics of a reaction. One other qualification is that while the amount of the heavy or radioactive isotope that is administered in an experiment may be small, it may be present in a low concentration in the natural isotope and in order to introduce enough to trace, one must administer a large amount of the element. If the total amount of the element administered is much greater than that usually encountered in the normal functioning of the body, the tracer will be distributed in an unnatural manner. Therefore, it is well to work with samples of tracers with the greatest enrichment or specific activity possible.

One other precaution is advisable in the case of radioactive isotopes. One should calculate the tissue dosage of radiation produced by the amount administered in order to keep the radiation level below the amount known to produce alterations in cell metabolism.

Both stable and radioactive isotopes have a wide range of uses for studying metabolism in living organisms and for diagnostic studies on humans. Obviously, however, only radioactive isotopes can be used for therapy; here the object is to bring

about deposition of radioactive material in the organ or tissue to be treated and so irradiate it selectively

There are three general techniques in use for studying metabolism by means of isotopes. In order to trace the distribution of 'heavy' or beta-emitting isotopes, it is necessary to remove tissues from the organism, process them chemically, and carry out the measurements on the chemical fractions. Some isotopes emit gamma rays and the distribution of these in the body can be measured in a semi-quantitative way by applying a Geiger counter to some external surface. Another method which yields very striking semi-quantitative results is the radioautograph technique: here the tissue or a section of it is placed in contact with a photographic film and the radioactivity present in any given area causes an exposure of the film in contact with this area. The tissue can then be stained and compared with the developed film to demonstrate the presence of the tracer in various regions of tissue.

The amount of tracer one needs to use depends on a number of biological factors and on which of the three methods of detection one wishes to use.

The isotopes which are of greatest use in biological and medical work are given in the table on page 148.

Isotopes of C, H and N have found their greatest use in studying the fate of organic molecules, i.e. in the study of intermediary metabolism. The last seven in the table are of use in tracing inorganic molecules, whereas isotopes of S and P and to a lesser extent those of O and I are used for studying the metabolism of both organic and inorganic molecules.

When one sets about labeling organic molecules for tracer experiments, the labeling must be done in the light of the in

Element	Isotope	Natural Abundance*	Nature of Radiation	Half Life
H	H ²	0.02%		
	H ³		β^-	31 yr
C	C ¹¹		β^+	20 min.
	C ¹³	1.1%		
	C ¹⁴		β^-	
N	N ¹⁵	0.37%		4000 yr.
S	S ³⁴	4.2%		
	S ³⁵		β^-	87 days
P	P ³²		β^-	14 days
O	O ¹⁸	0.20%		
Na	Na ²⁴		$\beta^+ \gamma$	14.8 hr
Cl	Cl ³⁸		$\beta^- \gamma$	37 min
K	K ⁴²		β^-	12.4 hr
Ca	Ca ⁴⁵		$\beta^- \gamma$	180 days
Fe	Fe ⁵⁵		K, e^-	4 yr
	Fe ⁵⁹		$\beta^- \gamma$	47 days
I	I ¹³¹		$\beta^- \gamma$	8 days

* This figure is given only for the stable isotopes

formation one wishes to obtain. In the case of deuterium which has been widely used for tracing organic molecules there are some positions in these compounds which it is useless to label with deuterium because it is so labile. These positions are anywhere the hydrogen is attached to an oxygen atom such as hydroxyl or carboxyl where the hydrogen is adjacent to a carbonyl group or where it is attached to nitrogen as in an amino or imino group. In the case of nitrogen it is useful to label the amino group of amino acids if one wishes to study their contribution to the nitrogen metabolism of the body but if one is interested in the fate of the carbon chain one must always be on the lookout for transamination which occurs in many tissues and transfers the amino group from one carbon chain to another. In most cases an oxygen isotope cannot be used

to study intermediary metabolism because of the high reactivity of most oxygen-containing groups in organic molecules. A very useful procedure is to use isotopes of two different elements to trace the same molecule; this procedure has proved to be very profitable.

Having planned one's experiments with these limitations in mind there are two possible modes of procedure, the choice between which may be influenced by the information desired.

A. The molecule in which one is interested may be synthesized in the laboratory or biologically with the isotope in a stable position and it is then administered to the living organism and its metabolic fate is traced by estimating the isotopic content of the excreta and tissues and perhaps in specific compounds in these.

B. The tracer isotope in some simple inorganic form (D as D_2O , O^{18} as CO_2^{18} , C^{14} as $NaHC^{14}O_3$, N^{15} as $N^{15}H_4^+$ etc.) is administered to the organism and its appearance in the body constituents is measured. This method has led to many interesting findings and from it labeled compounds may be isolated for future experiments of type A.

If one carries out one's research according to method A, a considerable amount of synthetic chemistry may be involved. One can avoid this by using a biological method of synthesis but although easy to carry out, this method is wasteful and should not be used unless the isotope is plentiful and cheap. The biological method of synthesis has one other serious disadvantage, and this is that it is very often difficult to know what is the position of the isotope in the synthesized molecule. However the biological method has one advantage in that valuable biological information may be obtained during the experiment.

A number of synthetic methods for introducing isotopes into

organic molecules have been developed, but these are too numerous to mention here. These problems become more numerous and difficult in the case of carbon tracers which are coming into a period of great usefulness in the study of intermediary metabolism

Before proceeding to a discussion of the use of tracers in strictly biological experiments their use in biochemical analysis may be mentioned.

Cl^{38} Has been used for studies of circulation in humans, and for estimating the permeability of cells to anions

Ca^{45} Has been used to some extent in determining absorption and excretion of calcium. Nearly all the Ca^{45} was deposited in bone and this deposition began very soon after administration. The rate of disappearance of the Ca^{45} from bone gives a good measure of the rate of metabolism of bone salt. Other problems where it would be useful are (1) mechanism of action of the parathyroid gland, (2) mechanism of action of vitamin D and (3) nature of the non-ionizable calcium of blood serum

Fe^{59} Whipple and others have used this isotope to obtain interesting and important information about hemoglobin formation and anemia. They found that after feeding inorganic iron, the iron appeared in the red blood cells within a few hours. They showed that anemic dogs absorbed fifty times as much inorganic iron from the gut as did normal dogs. They also showed that a low blood hemoglobin is not sufficient to bring about this increased absorption but that the tissue reserves of iron must be depleted. In this connection they found that muscle was the most important site of iron storage. The striking finding of this work is that iron is excreted to a very small

extent and that the amount of iron in the body is controlled not by excretion but by absorption

A great deal of work was done during the war on blood transfusion and Fe^{59} was of great assistance. It was used to measure the life of red blood cells in the body and to study the fate of red blood cells in stored blood which was subsequently used for transfusion.

I^{131} By the use of this isotope, it has been shown that thyroids of animals and of man can selectively concentrate iodine by a factor of 5,000 times over other tissues such a high specificity as this is unique in biological processes I^{131} emits a gamma ray and this has made it easy to study its rate of absorption and deposition in the body Sodium iodide containing I^{131} was fed to humans and the subject held in his hand a Geiger counter which was placed inside a lead box. The iodine was found to be absorbed rapidly and its rate of absorption was plotted. In animals radio-iodine could be detected in the thyroid gland a few minutes after the ingestion of sodium iodide. Radioactive iodine is proving to be of considerable clinical use especially in diagnosing thyroid disorders the patient is fed radioactive sodium iodide, a Geiger counter is placed on his neck, and the rate of deposition of iodine in the thyroid after oral administration is determined. It has been found that each of a number of different thyroid disorders produces a characteristic absorption curve. In connection with thyroid metabolism it has been found that the gland readily takes up the iodine of sodium iodide or diiodotyrosine, but not of thyroxine.

S^{34} and 35 These isotopes are among the most important for use in biological experiments Using them it has been pos-

sible to show that plants can incorporate the sulfur of inorganic sulfate into organic compounds but that animals cannot. Suppose that one wished to determine the amount of an amino acid say glycine, in a mouse's body. If one administered 10 milligrams of glycine with nitrogen containing 1 000% N^{15} to the mouse, killed it immediately and isolated from the carcass a sample of pure glycine with nitrogen containing 0 684% N^{15} , then the calculation is very simple. The natural content of N^{15} in nitrogen is 0 368 per cent, so the administered glycine had 0 632 atom per cent excess and the isolated glycine had 0 316 atom per cent excess therefore, the 10 milligrams administered must have been diluted by an equal amount from the mouse's body which therefore contained 10 milligrams glycine.

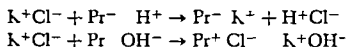
In adult animals in energy equilibrium the total amount the distribution and the chemical constitution of the body constituents are kept constant within narrow limits. The constituents of normal diets (proteins fats carbohydrates, inorganic ions etc.) are in principle the same as those which comprise the tissues and the experimenter can no longer identify them once they pass the intestinal wall and enter the blood and organs. As a result, very few of the earlier experiments were carried out with normal adult animals on normal diets, and the old knowledge of metabolism was based mainly on experiments conducted under such abnormal conditions that they permitted the accumulation of intermediates or end products, the use of unnatural compounds or of diets unduly enriched or poor in test substances experiments on poisoned or sick organisms or on isolated organs tissues or extracts. Such methods are usually by necessity indirect and often lead to erroneous conclusions.

Hewes was the first person to see the value of isotopes as biological tracers and as early as 1923 he used RaD as a tracer

to study the metabolism of lead in plants. And when heavy water first became available, he performed one of the most fundamental experiments on water metabolism in which he showed that the average time a water molecule spends in the human body is 14 days.

Since this early work of Hevesy's thousands of experiments have been carried out with isotopes for hundreds of different purposes. Since it will be impossible to mention any appreciable number of these, only some of the most interesting examples will be discussed, and the discussion can be limited to isotopes of C, H, N, S, P, Na, Cl, K, Ca, Fe, I.

Na^{24} and K^4 Brooks concluded from experiments on plant cells that when Na and K ions penetrated cells their concentration in various parts of the protoplasm was concerned with a temporary association with radicals of the protoplasmic protein molecules e.g.,

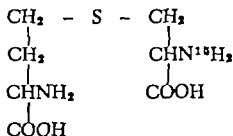


These experiments are especially interesting because of the difficulties which had previously beset such investigations and because they illustrate the simplicity of the tracer method. They show that the question of permeability becomes a matter of dynamic equilibrium involving understandable metabolic processes and there is no longer a necessity for postulating mysterious properties for cell membranes.

- Another important use for Na^{24} is the estimation of the amount of extra cellular fluid in tissues.

Isotopes of sulfur have been used to label methionine and demonstrate its conversion into cystine; this result was not very striking since it had been postulated before from other

evidence obtained without the use of isotopes. But du Vigneaud has recently carried out some experiments with S^{34} which elucidate the mechanism of this conversion. Du Vigneaud synthesized methionine with S^{34} and with C^{13} in the beta and gamma positions $CH_3-S^{34}-C^{13}H_2-C^{13}H_2NH_2-CH-COOH$. This was fed to rats and cystine was isolated from their hair; the cystine contained S^{34} but no C^{13} , showing that only the sulfur was transferred. He then synthesized cystathionine from homocystine and serine in which the N of the amino group of serine was labeled with N^{15} .



When this was cleaved by an enzyme present in liver, he isolated from the digest cystine with N^{15} in the amino group. Work such as this provides an example of the very great value of using more than one tracer simultaneously in the same problem.

S^{35} was used during the war to label the sulfur of mustard gas in an effort to elucidate the mechanism of action of this vesicant. However, in spite of the great deal of work done with this isotope, the problem remained unsolved.

One of the greatest contributions ever made to biochemistry and physiology was made possible by use of isotopes of H, N, C, and P to study intermediary metabolism. This work was begun by Schoenheimer with a study of deuterium-labeled fats and proteins, and later he used N^{15} as a tracer. As a result

of his pioneer work, a completely new concept of metabolism has arisen. Starting at about 1850 a number of theories were developed to explain the relationship between the foodstuffs of the diet and the chemicals making up the body. These were generally believed to behave independently except when small amounts of food constituents were used to replace "wear" and "tear" of tissues. But Schoenheimer showed that there was a vast range of interaction between foodstuffs and body constituents and he developed a new concept of metabolism. It has been stated as follows:

"As a result of Schoenheimer's investigations there has emerged a concept of metabolic regeneration wherein the central idea is the continual release and uptake of chemical substances by tissues to and from a circulating metabolic pool. Coincident with these cyclic processes, there occur among the components of the pool multitudinous chemical reactions of which relatively few are concerned with the elimination of waste products."

Some of the findings which have helped to elaborate this concept are given.

After feeding heavy water to animals deuterium rapidly appeared in nearly all tissue constituents. Therefore water could no longer be regarded simply as a solvent for chemical reactions in the body but its hydrogen and oxygen entered into chemical reactions in the metabolic pool. The exceptions to this finding were the amino acid lysine and the fatty acids linoleic and linolenic acids. These were found to be quite inert and therefore were not synthesized by the body but were essential constituents of the diet.

Fat Metabolism. By studying the rate of appearance of the deuterium of heavy water in fatty acids of the depot fats it

was shown that half of the fatty acids are regenerated in five to nine days, a very rapid turnover. This means that the depot fats are continually being broken down and resynthesized and their components are active in the metabolic pool. Also there is a continual interchange and interconversion between saturated and unsaturated fatty acids.

Studies with P^{32} showed that phospholipids even in brain and spinal cord are continually being replaced.

Cholesterol was thought to be a very stable chemical in the body but even this was half regenerated in 15 to 25 days, and from the deuterium content it could be shown that cholesterol was formed from smaller units of about three carbon atoms in the metabolic pool.

Protein Metabolism If amino acids containing N^{15} are fed, only one-half of the N^{15} is excreted and the rest is found in the body proteins. Three days after feeding leucine containing N^{15} only 30 per cent of the tracer was left in the leucine of the body proteins, 20 per cent was in other amino acids, and 50 per cent had been excreted. The same result was obtained with tyrosine containing N^{15} . This amino shift was found to be of general occurrence and fairly rapid. Tracer studies showed that it probably took place through alpha keto glutaric acid and this is one bridge between protein and carbohydrate metabolism. If these reactions go on as these experiments indicate, it means that tissue proteins are continually being broken down and resynthesized and are not the static entities they were previously thought to be.

Phosphorus Metabolism As a result of work with P^{32} it was shown that even such rigid structures as bones and teeth are in a state of dynamic equilibrium. Hevesy showed that in young cats there was an appreciable uptake of phosphate by

the teeth in a few hours and it was further determined that in 250 days 1 per cent of the phosphorus of teeth exchanges with phosphorus of the metabolic pool. The turnover of phosphate by bone was shown to be more rapid than this.

Carbohydrate Metabolism. One of the earliest findings here, made by Schoenheimer was that if animals were fed heavy water the deuterium content of the glycogen formed was much greater than could be accounted for by the simple condensation of hexoses which was previously assumed. This means that the reserve stores of glycogen in the body must be formed from smaller units and work with C^{11} has shown that lactic acid is one of the materials from which glycogen is synthesized.

Excretion Products It has been found that CO_2 is not simply an excretion product but that it is an active constituent of the metabolic pool and it can be assimilated rapidly by mammals. For instance, soon after the administration of CO_2 as $NaHC^{11}O_3$ the C^{11} appeared in liver glycogen. Further experiments are now demonstrating that the carbon of administered CO_2 appears in a very large number of body constituents and that CO_2 participates in nearly all reactions of the metabolic pool.

When creatinine or urea the urinary excretion products of protein metabolism were labeled with deuterium or N^{15} and fed to animals the tracer did not enter other body constituents which means that these are true excretion products and when once formed no longer take part in biochemical reactions.

Now especially with carbon isotopes available a large number of tracer studies are being directed to filling in the details of this picture which I have sketched. As you can readily appreciate, there is an almost infinite number of interconversions

taking place in the metabolic pool, and it is these reactions which are receiving the most attention

In conclusion it should be pointed out that it has been the purpose of this chapter to demonstrate by a few selected examples what a powerful and versatile method isotopes have placed in the hands of the biological researcher. Many examples have also indicated how this method has not brought about as great a revolution as one is sometimes led to believe; it is better regarded as just another tool at the command of the present-day biologist to be used when it will avoid labor and ambiguity in solving a problem that is under investigation in the normal course of biological research.

CHAPTER XII

THE MEDICAL USES

OF ATOMIC ENERGY¹

BY C P RHOADS²

WHAT can we accomplish today in the application of radioactive isotopes in the treatment of disease? My feeling is that, at this moment, isotopes of only two elements have been proved to be therapeutically useful radioactive isotopes of iodine and phosphorus.

Curiously enough, each one of these two elements has been shown to be useful in the treatment of one noncancerous medical disorder and one form of cancer. That is radioactive iodine has been proved to be effective in the treatment of a disorder of the thyroid gland associated with overfunctioning of that gland and poisoning of the body. Radioactive iodine is capable

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of restraining this overactivity, bringing functions to normal, and so relieving the patient of symptoms. The application of iodine in the treatment of cancer of the thyroid gland I will discuss. In the case of phosphorus there is a very real use in treating a noncancerous disorder of the blood forming tissues, a disorder marked also by overfunctioning, which can be restrained by the use of radioactive phosphorus. There is also a set of cancerous disorders of blood formation known as leukemia, which again can be restrained in certain specific instances.

The work with iodine began in a rather quiet way in the late 1930's and one of the earliest studies was that of Hertz and his associates in Boston who prepared iodine by the exposure of ethyl iodide to radium mixed with beryllium. The activated iodine was injected into rabbits. Then the various organs of the recipient animal were removed, minced, spread in a mush on a plate, and exposed to standard detection techniques. In this way it was possible to show that, as had been expected, the thyroid gland picked up when normal, about 80 times as much iodine as was picked up by any other normal tissue. This result is still valid. Furthermore, the fact was shown that, if the thyroid gland was stimulated by such factors as pregnancy or else by the administration of materials which lead to overactivity of this gland, the pickup of iodine might reach a level several hundred times that found in normal tissue.

The thyroid gland is located in the neck and has the very important function of selecting iodine from the blood stream and of converting the iodine to a compound known as thyroxin which is active in maintaining a specified rate—the rate of oxidation of live tissues—of oxidation of the tissues. When an excess of thyroxin is formed, the metabolic rate increases to a

point where severe symptoms of poisoning and death may result. This disease can be controlled in many instances by the removal of the source of the poison—the thyroid gland or a large part of the gland. This involves a procedure which is at best troublesome and unpleasant at worst hazardous—possibly to a great degree. Hence, any procedure which allows the control of overthyroid function without surgical operation is a matter of great importance to medicine.

The experiments of Hertz showed not only that the active thyroid gland picked up more iodine than the normal thyroid gland, but also that the curve of pickup was quite different. Furthermore, certain different types of overactivity could be elucidated specifically by examining the rate of uptake of iodine in these beautiful experiments. Once these points had been clear the next logical step was to use radioactive iodine, prepared by the cyclotron method and then becoming available, to study the uptake of iodine by the thyroid gland of human beings.

A good deal of very complex work was involved. Precise indexes had to be established by which the pickup per unit of tissue could be settled. This was done and then studies were made on man. The earliest set of reports—or one of the earliest, was by Hamilton and Soley of the University of California—a report by Hertz appeared about the same time.

Hamilton reported on 22 patients in 1939, 22 patients with overactivity of the thyroid gland treated by radioactive iodine and studied for the extent of the pickup of this active element by the thyroid tissue. He made a very important observation later confirmed by Hertz, that the iodine actually goes to form the toxic material which is made by this gland. In other words the iodine takes part in the natural metabolic processes of this

important organ, this fact is a notable contribution to our knowledge.

Furthermore, Hamilton reported on two patients who had cancer of the thyroid gland. The evidence suggested that the cancer shared the ability of the tissues from which it sprang to pick up iodine. The findings, of course, led to the possibilities that one had (a) a method for controlling overactivity of the gland and (b) a method of controlling, perhaps cancer of the gland.

Two papers appeared from the Boston investigators, one by Hertz and Roberts and the other by Chapman and Evans who picked up the work when Hertz left for the war. These papers deal with the results of the study of some 50 patients with thyroid overactivity. Detailed studies were made, the precise retention of iodine by the gland was established, and the precise degree of control of gland activity was made clear and factual. It is possible to say that today on the basis of well-established data, this disorder may be controlled in about 80 per cent of the patients by giving radioactive iodine. This is a very important advance.

One precaution was not observed, as far as I am aware. I am not certain that sufficient experiments have been done to establish the limits of safety of the use of radioactive iodine in the treatment of thyroid disorders. One must always recall that, in dealing with materials of this type, sufficient energy may be liberated over a sufficiently long period to make cancer occur. It is a very curious anomaly that the agents with which we deal in treating cancer are also under certain circumstances able to cause cancer. I am very hopeful that studies will be made now on an extensive scale to establish the amount of radiation delivered by iodine to the thyroid gland which can be tolerated

without the induction of changes which may become cancer in that organ.

In short, one can control hyperthyroidism by the use of radioactive iodine. There is a little debate about what dose is desirable and a little debate upon the duration of control, but I think for the purpose of a general statement one can assume that the case is proved and control is possible.

The use of radioactive iodine in the treatment of thyroid cancer is a much more difficult matter and I think I am justified in discussing what we know about the nature of cancer. Recall that cancer is the growth from a normal cell of a distinctly abnormal one which shares in appearance, structure, and functions certain of the characteristics of the cells from which it sprang but which differs somewhat from the parent structure. These differences can be established in a variety of ways and they may be of greater or lesser degree. We have no really precise means for measuring how different the functions of the cancer cell are from its maternal parent.

Thyroid cancer is more than a single disease. This disorder marked by a wild, uncontrolled overgrowth of thyroid gland cells may take a variety of forms discernible under the microscope. Mr. Marinelli and Dr. Foote of Memorial Hospital among others, have made careful studies of the quantitative pickup of radioactive iodine by the several forms of cancer of the thyroid gland and also by certain noncancerous or benign tumors of that organ. They have done a great deal to correlate the cellular picture of thyroid cancer with its ability to pick up iodine. It is a very interesting thing that, as the cancer cells become more and more unlike their parent cells they simultaneously lose to a greater and greater degree the ability to share with the parent cells the function of selecting

iodine and concentrating it in their bodies. In other words the more malignant, the more vicious the more widespread and destructive the cancer is the less by and large, is its ability to pick iodine out of the bloodstream and to concentrate it in the cellular structure.

It happens that some years ago at the Montefiore Hospital in New York two patients were studied who had cancer of the thyroid gland and had very extensive localized deposits of the cancer tissue in various parts of the body far removed from the parent tissue—what we call metastases. Of these two patients one had had the thyroid gland, the site of the original cancer removed surgically but still had manifestations of an overactivity of the thyroid. This was clear evidence, of course, that the extensions of this cancer shared the functions possessed by the parent gland of manufacturing thyroxin the toxic product formed by the gland normally. This suggested that, since thyroxin contains iodine, the cancer metastasis or localized deposits would pick up radioactive iodine and perhaps in sufficient quantities to allow control of the growth.

Indeed, in this instance, when iodine was given as a tracer and a Geiger counter passed over the body, deposits of cancer were detected which had not been visualized by ordinary x-ray methods. This was a very unusual case and a beautiful one for experimental study. I believe that Mr. Marinelli, Dr. Leiter, Dr. Seidlin and their associates made a very distinguished contribution. It was possible to show that the conventional method of suppressing the thyroid activity in this patient also suppressed the activity of the localized disseminated deposits of the thyroid cancer and further that the iodine was picked up in good concentration by these localized deposits. Then finally the crucial experiment was made under Mr. Marinelli's

direction the patient was treated with radioactive iodine and a pronounced therapeutic effect was obtained. Indeed, now some years later the patient still appears to be under good control. The tumor is still there but, as far as one can tell, it is no longer active. A very dramatic and a very exciting case. However this point must be made, thyroid cancer takes many forms. Certainly not more than 15 per cent of all thyroid cancers—a rare disease in the first place, has been shown to pick up appreciable amounts of radioactive iodine. One form, and a rather unusual form, can be depended upon to pick up iodine. The more malignant and destructive forms tend to pick up to a lesser and lesser degree as the invasiveness increases.

I personally cannot feel hopeful that we will have by radioactive iodine, straight inorganic iodine, an attack on a very large percentage of thyroid cancers. The beautiful work done on the single case I have discussed and the excitement associated with any new method of treatment have tended to obscure the fact that only a very small percentage of all thyroid cancers pick up radioactive iodine at all, and only a very small fraction of those pick up amounts adequate to allow one to expect to control the disease.

However I don't wish to appear overpessimistic. I'd like to point out that we have only scratched the surface of this problem. Efforts should be undertaken to incorporate radioactive iodine in organic compounds that may be picked up to a greater extent by the abnormal, cancerous tissue.

To summarize, radioactive iodine is useful in the treatment of hyperthyroidism but I think that we do not yet have adequate data on the hazards. Therefore, until we have more information, I will preserve a conservative position in predicting the extent of the future use of that material. In the treatment

of thyroid cancer only a small percentage of the cancers pick up iodine at all and only a small fraction of those pick up enough to allow us to expect a therapeutic effect of the radioactive element. But still the first bridge has been crossed, one can control specific examples of the disease.

Early in the work with isotopes Dr John Lawrence of the University of California and others began to explore the possibility that phosphorus could be used to measure the rate of growth or the rate of chemical turnover of normal and cancer cells. This of course was thought possible because phosphorus is an active participant in the metabolic processes.

Dr Lawrence published originally a very dramatic experiment involving the use of radioactive phosphorus in the study of leukemia in mice. I should like to point out that leukemia is a term which includes a number of sub-groups. It is a cancer of the blood forming tissues but, since there are several different types of blood-forming tissues, there are several different types of leukemia. They are all fatal, but they vary in their clinical manifestations and in their response to therapy.

The results obtained by Dr Lawrence proved that the lymph glands—the glands in one's neck that swell when one has a sore throat, if they were the site of cancer (leukemia) picked up more radioactive phosphorus than did the normal glands. That led to an elaborate series of studies on animals with leukemia of various forms and then on human beings with leukemia to establish how great a difference in pickup existed between normal tissue and tissue which had become cancerous (leukemic). It was learned that the pickup of phosphorus was dependent really upon a number of factors. One factor is the amount of phosphorus which normally is deposited in tissue. For example, bone, which is made up very largely of calcium

phosphate, will in time deposit a large amount of radioactive phosphorus but it is turned over very slowly. This leads to a second factor—the metabolic turnover of phosphorus—and that is very important because rapidly growing cells use in their metabolic activity much more phosphorus than do less actively growing cells.

Cancer cells by and large, are very rapidly growing cells and so the very early observations gave very promising results. They indicated clearly that cancer cells in general tended to pick up more phosphorus per cell than did analogous normal cells. These early experiments in my opinion were not adequately controlled, because normal tissue was not compared with cancer tissue having the same rate of growth. The cancer tissue was compared with normal tissue of a lesser rate of growth. Since this factor of growth rate was not adequately controlled, the early figures were more hopeful than the later information warrants. But, in any event, the fact was clear that phosphorus was picked up by leukemia tissue. The pickup depended on the chemical activity of the cells—the activity in general correlated with the rate of growth, and the cancer in general grows more rapidly than normal tissue; hence there was more phosphorus in the cancer cells than in the normal ones. This was particularly true of the cancer cells of the blood-forming tissues—the bone marrow—the spleen, and the lymph glands.

These facts promptly led, of course, to experiments designed to cure cancer of blood-forming tissue by the use of radioactive phosphorus. You should understand that there are two types of cancer of blood-forming tissue. One type concerns a group of white blood cells, normally the defensive cells of the bloodstream formed principally in the bone marrow. A cancer of these cells can occur known as myelogenous leukemia. The

cells then grow without restraint, infiltrate all tissues of the body and lead to the death of the individual affected. These cancer cells share with the normal form the property of picking up large amounts of radioactive phosphorus or, of course, phosphorus of any type, and are somewhat more active in this function. In this way, a high concentration of radioactive phosphorus can be set up in the cancer cell, which thereby poisons itself and commits suicide very handily for us. So far some 150 patients have been treated for this disease with radioactive phosphorus.

To sum up the results it may be stated that rather uniformly the growth of the cancer cells can be restrained to some extent, the symptoms of the patient can be lessened but life probably is not prolonged. Certainly life is not prolonged by more than two or three months. The phosphorus is somewhat better from the point of view of the patient than is the use of conventional x ray treatment, because there is less radiation sickness involved, but a real hazard is associated with the use of phosphorus. We are dealing here with an element with a half life of fourteen days and it is not possible to predict precisely how sensitive are the cancer cells or exactly how much phosphorus they will pick up. It is almost impossible to predict precisely how much normal blood-forming tissue is present in the body. Therefore, it is hard to arrive at a dose which is just right to control the cancer cells and will avoid serious or perhaps fatal damage to the normal blood-forming tissues of the body. For that reason a tendency in most institutions is to discard the use of phosphorus and to stick to conventional x rays as being somewhat safer and more predictable in its results and attended by less hazards to the patient, even though it does cause some illness in the course of treatment.

The second form of leukemia, known as lymphatic leukemia is a cancer of another type of white blood cells. It also kills uniformly, and somewhat more quickly than does the myelogenous form. It is of particular concern to us all because it is a form which frequently affects children. There have been extensive studies on the use of radioactive phosphorus in the treatment of lymphatic leukemia and the results are not promising.

About 160 patients have been studied carefully and the results have been summarized. These experiments have been made in a number of clinics all very good, and it is quite apparent that the results are rather unsatisfactory. Of all the patients with the chronic form of lymphatic leukemia only about 50 per cent show any measurable benefit from this procedure. The other 50 per cent are not benefited at all. Furthermore, the benefit exerted is at best transient since there is little or no prolongation of life. And, finally there is a factor of hazard. Radioactive phosphorus once it is in the body cannot be removed. The precise sensitivity of the normal tissue, which picks up phosphorus almost as well as the cancer tissue, cannot be predicted. The tendency is to abandon the use of radioactive phosphorus and to revert to the more conventional x-ray treatment. Even though the x-ray treatment requires cumbersome equipment and is associated with some illness on the part of the patient, it is somewhat more controllable.

Until we have better compounds of radioactive phosphorus than those now used the treatment of chronic lymphatic leukemia does not promise dramatic results in the near future. In the treatment of acute lymphatic leukemia there is no good result whatever and it is distinctly hazardous.

To summarize briefly there are two forms of leukemia. In

myelogenous leukemia, some relief can be obtained, life is not prolonged and there is little advantage in the use of phosphorus. In lymphatic leukemia, there is no advantage in phosphorus; life is not prolonged, and the hazard is real. I am not optimistic about the future of the use of inorganic radioactive phosphorus in the treatment of cancer of the blood-forming tissues.

There is another disorder of blood-forming tissues which is not a cancer and which is known as polycythemia. In this condition, the formation of red blood cells is abnormally rapid. It is not a fatal disease. It is a metabolic abnormality attended by serious symptoms, great disability, and eventual complications which may lead to death. Here the picture is quite different from that of leukemia. In the case of polycythemia, radioactive phosphorus is an excellent therapeutic agent. Doses in the range of 2 to 4 millicuries result in the disappearance of symptoms which lasts for up to two years without further treatment. The patient is enormously relieved. There is objective evidence of improvement and by every point of view in treating this disorder the use of radioactive phosphorus is the method of choice.

The two noncancerous conditions—hyperthyroidism and polycythemia—are accessible today to treatment, the first with radioactive iodine and the second with radioactive phosphorus. The two cancerous conditions—thyroid cancer and cancer of blood-forming tissues—are not proved to be very accessible to cure or to control by the use of radioactive iodine in the first case or of radioactive phosphorus in the second case.

Now what does the future hold?

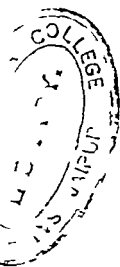
To have expected inorganic elements to be picked up so selectively and concentrated so adequately by cancer tissue as

compared to normal tissue was a very optimistic hope. I am not surprised that we are somewhat disappointed but we have a vast field before us. We are beginning to study the selective pickup by cancer of a vast variety of organic compounds which can be synthesized in the laboratory of organic chemistry to contain radioactive isotopes of a variety of elements. I am very hopeful that startling discoveries will be made in the years to come—not next year or the year after but in five, ten or fifteen years.

I can give you examples of what sort of thing is in progress. It is possible that cancer tissue contains somewhat different proportions of amino acids than does normal tissue. Experiments are under way to synthesize amino acids containing radioactive elements. It could be hoped if one cares to be very optimistic, that one could in this way lead into the cancerous tissue, by its affinity for certain organic constituents quantities of radioactive materials which would lead to an auto-intoxication and death of the cancer tissue. Similarly much cancer occurs in organs which are under the control of the sex hormones—the breast and the uterus in women and the prostate gland in men. These organs depend for their very existence on compounds of known chemical constitution. It is believed that they selectively concentrate these compounds or hormones when they are administered. Efforts are now under way to synthesize in the laboratory sex hormones containing radioactive elements.

Finally and this must not be overlooked there is the tremendous fundamental work which will be done in a study of the basic biochemistry of the body by the use of radioactive tracer elements. I feel there has been far too much emphasis on the direct therapeutic application of the isotopes now in

existence and far too little emphasis on the enormous developments out of which will come a new era of knowledge of the fundamental chemical processes of the body through the use of tracer elements which atomic energy provides. Through that study a vista opens up about which it is really most inspiring to think.



CHAPTER XIII

RADIOACTIVE TRACER TECHNIQUES IN PHARMACEUTICAL RESEARCH¹

BY JOHN E CHRISTIAN²

THE PROGRESS of science is characterized by the discovery and use of relatively few instruments or tools for application in research. Examples of such instruments are the analytical balance and the microscope which, when discovered, advanced science rapidly. Within the last fifteen years however two very useful instruments have been developed, the cyclotron and the chain-reacting pile. The cyclotron is capable of producing high speed particles of matter of various descriptions and the pile of producing slow neutrons. The products of these instruments radioactive isotopes are new tools in the hands of the scientists.

¹ By permission from the *Journal of the American Pharmaceutical Association*, material in this chapter is taken from Vol. XXXVII No. 6 June, 1948.

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It has been stated that the range of usefulness of the products of the cyclotron and the pile is unsurpassed by any other tools at our disposal with the possible exception of the analytical balance and the microscope.

Pharmacy as a profession is chiefly the application of all branches of science to the production of medicinals and medicinal products, and since radioactive isotopes are applicable to all branches of science, isotopes have particular application in the various divisions of the pharmaceutical profession. In view of these facts the pharmaceutical profession should be quick to awaken to the unique opportunities afforded by radioactive isotope "tracer" techniques.

Isotopes have many important uses in the various fields of science such as development of power and atomic research; however the pharmaceutical profession is primarily concerned with the use of products which are radioactive.

APPLICATIONS

Radioactive products have at the present time two very outstanding applications to pharmacy and pharmaceutical research (1) as therapeutic agents when used properly and with necessary precautions, and (2) as tracer elements. As therapeutic agents radioactive isotopes by virtue of their radiations are, in the true sense of the word a drug, and are so classified and regulated under Section 505 of the Federal Food, Drug, and Cosmetic Act.

The particles emitted when the isotope disintegrates are a source of penetrating radiation in the treatment of abnormal tissues, a circumstance in which the injury to unwanted tissue is notably greater than to normal essential tissue.

Radioactive Isotopes in Pharmaceutical Research In pharmaceutical research the use of radioactive isotopes in therapy offers several possibilities. Specific localizing compounds which, by preferentially localizing in diseased tissue, will result in much greater radiation damage to the diseased than to normal tissue, need to be prepared and tested. A few such studies have been made, examples of which are iodine and certain gold colloids but a great variety of compounds and information concerning their concentration in various tissues should be investigated. Perhaps much of this information may be forthcoming from data obtained from other studies.

A second possible application of radioactive isotopes concerning therapeutic agents is the production of modified forms of materials commonly prepared by manufacturing pharmacists. The effects of radiation in the production of modified strains of bacteria, viruses, fungi, and actinomyces and such effects as the denaturation of proteins and inactivation of enzymes should be studied.

A third and very important study is that of the nature and method of treatment of radiation damage. In this direction drugs and necessary treatment should be developed to prevent or lessen radiation damage and sickness. This study is important for cases of possible human overexposure in radiation therapy, atomic energy work, and warfare.

Radioactive isotopes have already been used as diagnostic agents; however, much remains to be done toward extending this usage.

In regard to therapeutic usage of isotopes there is little direct commercial application in which the pharmacist, or manufacturing pharmacist, will be interested since there is no immediate prospect of the use of isotopes in medicine in large

amounts. The conditions in which isotopes have particular value therapeutically are rare at the present time and in such cases the dose is small and varied. The discovery of specific localizing agents as mentioned above might change this picture appreciably.

Application as Tracer Elements Radioactive isotopes, as tracer elements rather than as therapeutic agents, have the principal applications to pharmacy and pharmaceutical research at the present time. A radioactive isotope of an element behaves identically with other isotopes of the element in all chemical and physiological processes. It labels without question the particular atoms one wishes to trace regardless of their incorporation into units with other atoms or into any combination in which one might desire to trace them. In other words we have the ultimate in specificity for the tagging of an atom or element.

The advantages of the use of radioactive isotopes as tracer substances may be listed

- 1) The movement of tagged substances is easily followed using suitable detection devices
- 2) Small amounts of the tagged substance may be used. As an example, as little as 10^{-7} gram of iodine, 0.1 microgram, is sufficient for the tracer technique using radioactive iodine.
- 3) It is often unnecessary to remove organs or tissues or to kill the organism in order to determine the presence and content of radioactive material.
- 4) The detection of elements by their radioactivity is up to one million times as sensitive as by the usual methods of chemical or physical analysis. This means that roughly 10^{-18} to 10^{-20} gram of substance can often be readily detected.

Such sensitivity of measurement makes possible the intelligent study of problems which heretofore could not be solved by the use of existing methods or tools. In pharmacy and in pharmaceutical research in particular we have many problems which lend themselves to the application of radioactive isotopes and which cannot be adequately solved by other existing methods.

Pure Pharmacy Research. As a tool in pure pharmacy research, radioactive isotopes have widespread application. A few of the possible applications may be briefly mentioned here as illustrations of this point.

Researchers have long desired to know the rate of absorption of certain medicaments from various bases so that bases could be classified in this respect. Also it is desirable to know if certain medicaments pass through the normal skin and membranes at all and if so to what extent. Since such small amounts of materials are involved, isotopes offer about the only method of measuring such absorption. The rate of absorption of certain substances varies with the degree of irritation of the skin, thus the need for a method of measuring skin irritation is apparent.

The disintegration rate of tablets and enteric-coated pills and tablets *in vivo* may be most critically studied using radioactive isotopes. The problem of exactly when and where an enteric coat breaks down in the animal body is of considerable importance in determining the relative efficiencies of the various enteric coats.

The pharmaceutical profession has a variety of methods for the administration of a specific medicinal substance. The question of just which type of preparation gives the most satisfactory absorption or utilization of the medicinal can now be deter-

mined precisely by means of the tracer technique. These are but a few of the many examples which might be cited for the use of isotopes in pure pharmacy research

Tracer Technique in Pharmacology In pharmacology as applied to pharmacy the tracer technique offers even greater possibilities for study

Wherever one desires to measure small amounts of substances this technique is particularly applicable. The determination of small amounts of residues on the skin and of the effect of various solutions upon the calcium-phosphorus depletion of teeth are excellent examples of tracer application. Studies such as these are next to impossible without the isotope tracer technique.

One of the greatest advantages which isotopes offer in pharmacology is making possible a study not previously feasible, of the rate of absorption, excretion alteration breakdown concentration in the blood, and per cent distribution in various organs of almost every synthetic medicinal substance. The same type of study may also soon be done with certain natural substances which are not readily synthesized since a plant farm designed to grow plants in an atmosphere of radioactive CO_2 is now being set up in Chicago. This unit is being designed to produce natural drug principles containing radioactive atoms. To trace in the body such substances as vitamins hormones antitoxins and drugs which distribute themselves in tissue in minute quantities is impossible by ordinary analytical procedures. The value of such studies cannot be predicted however one can say that undoubtedly the contribution will be much greater than can be anticipated. Even the study of such a simple substance as ethyl alcohol would be a valuable contribution to pharmacy and medicine.

By use of the radioautographic technique more detailed tracer studies can be made, determining exactly in what cells within a particular organ the substance being studied concentrates.

Radioactive isotopes also lend themselves to toxicity studies a major area of pharmacological study.

The study of the uptake, utilization, storage, mechanism of action, and need in the animal body of certain trace elements such as Cu, Co, Ni, and Cr is now possible by the tracer technique. In short, we may say that radioactive isotopes are applicable to almost every pharmacological problem.

Practical Applications in Pharmaceutical Chemistry In the field of pharmaceutical chemistry the applications of radioactive isotopes are concerned primarily with the synthesis of substances which contain radioactive atoms which may then be traced. Such syntheses require special techniques and precautions but are not considered difficult or dangerous.

The applications of isotopes in pharmaceutical chemistry however are not confined to synthesis. Radioactive isotopes offer the most sensitive quantitative method known and as such, provide a number of practical applications. The determination of the solubilities of very slightly soluble compounds is not possible to the same degree by other existing methods. The use of isotopes for such determinations possesses the advantage that the presence of foreign ions in no way interferes with the measurements. The method may be applied without difficulty for example, in determining the solubility of lead sulfate in the presence of calcium sulfate. The determination of the amount of a given substance that is absorbed or occluded during a precipitation or purification procedure offers considerable application. The determination of mere traces by ordi

nary chemical analysis when it can be accomplished at all, requires tedious methods and is time consuming. Isotopes also lend themselves to a study of the behavior chemical reactions, and properties of medicinal substances of unknown properties.

Colloids are extremely important in pharmaceutical and medicinal chemistry and radioactive isotopes are ideal for their study from almost every standpoint. Such studies would reveal considerable information about colloids which is not used or known today

In conjunction with coprecipitation elution added carriers, and chromatographic absorption procedures, it will be possible to isolate, purify and identify substances in small amounts from complex mixtures which heretofore was not possible. Such procedures used along with pharmacological studies will be invaluable to pharmaceutical chemical research.

Research Area in Pharmacognosy In the field of pharmacognosy there are likewise many opportunities for applications of radioactive isotopes. Here again a few examples will suffice to illustrate the use.

Of prime importance at the present time is the production of natural plant products which are radioactive. With many alkaloids glycosides etc. this is possible only by the growth of plants from which these materials are obtained in an atmosphere of radioactive carbon dioxide or in a media containing the desirable tagging atom. The problems of production and isolation of such principles fall within the scope of the pharmacognosist. The use of radioactive isotopes in conjunction with the field of hydroponics offers a most fertile field for the production and study of natural plant medicinals. A study by the radioautographic technique of just what plant cells contain the active principles and at what periods the content is greatest

in the various cells would be invaluable. The pharmacognosist can contribute to the production of radioactive antibiotics which in itself is an important research area. The rate of uptake, distribution and elimination of various elements radicals and compounds in medicinal plants is a research project worthy of considerable study especially in conjunction with the effect of various substances upon the active principles produced by the plant.

A study of the need of medicinal plants for certain trace elements and fertilizer needs likewise can now be investigated more thoroughly using the tracer technique.

Radioactive isotopes may also be applied to solve certain manufacturing problems examples of which are the uniform distribution of drugs in various medicinal forms mixing problems and various quantitative problems

SUMMARY

Briefly we may say that radioactive isotopes are applicable to all branches of pharmaceutical research and, by virtue of the very nature of pharmaceutical problems themselves, are especially important.

It is hoped that the illustrations of the applications of radioactive tracers to pharmacy and pharmaceutical research, as presented here, are of sufficient number and variety to show that this tool is capable of many diverse applications

It is desirable that in the future a greater number of individuals interested in pharmaceutical research and the welfare of pharmacy make use of this excellent research tool and thereby facilitate the solution of many important pharmaceutical problems

CHAPTER XIV

NUCLEAR PHYSICS

AND MEDICAL RESEARCH¹

BY G FAILLA²

UNDOUBTEDLY there will be later very important developments in nuclear physics which at present cannot even be imagined. When Roentgen discovered x rays he soon found that a photograph of a human hand taken with the new rays revealed the contour of all the bones. After that it was not hard to imagine how with improved apparatus and further study x rays would become very useful in the diagnosis of disease. However no one at that time could have possibly predicted that x rays would play an important part for instance, in the development of synthetic rubber or nylon. That came about simply because some physicists were curious about the nature of the new rays.

¹ Reprinted by permission from *The Journal Lancet*, Vol. LXVII, No. 2, February 1947.

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Were they waves like light? If so it should be possible to obtain diffraction patterns by passing them through a crystal argued von Laue. Friedrich and Knipping tried it and found it so. Many new discoveries followed this observation. Then the process was reversed and x rays were used to study crystals then to study the structure of all sorts of materials. Chemists learned more about the shape of molecules and how to alter them to produce desirable characteristics such as stretching in the case of rubber. Today the x ray spectrometer is an indispensable research tool in every industrial laboratory.

From the work that has already been done with radioactive isotopes and other tools of nuclear physics it is obvious that they will be very valuable in medical research. But physicists, chemists, biologists, and all sorts of people will try innumerable experiments to satisfy their curiosity about something or other in connection with these tools and some of them will discover new phenomena that will expand the field in different directions—totally unpredictable at present. It is very important, for this reason that "free" research, untrammelled by directives or utilitarian objectives be encouraged and nurtured.

The widespread use of radioactive isotopes involves health hazards of an insidious nature. Ionizing radiations which they emit, injure living tissues but at the time of the exposure the individual has no sensation or warning of any kind. Furthermore the injury does not manifest itself for days, weeks, months or even years. In fact if the injury occurs in the germ cells it may become apparent only in subsequent generations. Enough is known today to prevent direct injury to anyone working with ionizing radiations. Less but still a good deal is known about the distribution of radioactive isotopes taken into the human body and the injuries they may produce through the radiations.

they emit. Great caution must be exercised when radioactive substances *per se* or in chemical compounds are introduced into the body for any purpose whatever. We must avoid the tragic results that followed the drinking of radium water, which at the time was advertised as a magic remedy for many obscure ailments. It is important to remember that in these cases, no injurious effects were noted for a period of years and then cancer developed.

As you all know carbon is a chemical component of practically every drug produced today. A radioactive isotope of carbon, C^{14} is now available and in principle it may be incorporated in any organic compound. Food—let us say sugar—or a drug containing some radioactive carbon may be administered to a person to study its course through the body. C^{14} has a very long life (after 4,000 years about one half of the initial amount still remains) so that if it is not eliminated completely by the body some at least will continue to irradiate tissues throughout the individual's life. What will happen depends on the amount retained and its location. There is practically no experimental information available on this point. For this reason the committee on isotope distribution set up by the Manhattan District has recommended that no C^{14} is to be administered to human subjects until sufficient animal experimentation will have provided the basis for safe use.

Carbon fourteen presents other difficulties. If it becomes incorporated in living tissues some will be transformed into CO_2 through ordinary metabolic processes and will be exhaled into the atmosphere. In a laboratory where many experimental animals are present, this may constitute a health hazard for the workers. At any rate the presence of a radioactive gas in a laboratory where delicate radiation instruments are used is very

undesirable. Therefore, provisions should be made to remove CO_2 from the air

It is certain that radioactive isotopes will be used in the future for all sorts of purposes. They will be used because of the fact that they emit radiation. Human beings have been exposed from time immemorial to the radiations of radioactive substances in the earth and to cosmic rays but the intensity of these naturally occurring radiations is very low. If by the wide spread use of atomic power and radioactive isotopes we raise the level of ionizing radiation to which the population is exposed, we shall have to consider seriously the influence on future generations. Exposure to ionizing radiation has a cumulative effect on the germ cells. Mutations in the vast majority of cases produce inferior individuals. We must indeed be wise in the Atomic Age to avoid sudden extermination in an atomic war or slow deterioration and possibly eventual extinction of the human race.

APPENDIX

APPENDIX A

CHRONOLOGICAL LIST OF HIGHLIGHTS SIGNIFICANT TO ATOMIC ENERGY

- 1687 Fundamental Laws of Motion Defined and Atomic Theory Revived (I. Newton, England)
- 1803 Atomic Theory Formulated (J. Dalton, England)
- 1869 Periodic Table Arranged (D. Mendeleeff, Russia)
- 1895 X Rays Discovered (W. K. Roentgen, Germany)
- 1896 Natural Radioactivity Discovered (A. H. Becquerel, France)
- 1897 Electron Discovered (J. J. Thomson, England)
- 1898 Polonium and Radium Isolated from Uranium (Marie and Pierre Curie, France)
- 1900 Quantum Theory Originated (M. Planck, Germany)
- 1905 Radioactive Decay Theory Developed (E. Rutherford and F. Soddy, England)
- 1906 Alpha Particle Discovered (E. Rutherford, England)
- 1911 Special Theory of Relativity of Matter and Energy (Relativity) Formulated (A. Einstein, Germany and United States)
- 1913 Bohr's Atomic Model Formulated (H. Bohr, Germany & Rutherford, England)
- 1927 Electron Charge Measured (R. Millikan, United States)
- 1928 Neutron Atomic Discovered (J. Chadwick, England)
- 1929 Carbon-13 Isotope Discovered (C. D. B. Walling, England)
- 1931 First Artificial Radioisotope Produced (S. D. D'Amico, United States)
- 1932 Artificial Radioisotope Produced (S. D. D'Amico, United States)
- 1934 Artificial Radioisotope Produced (S. D. D'Amico, United States)
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- 1982 Artificial Radioisotope Produced (S. D. D'Amico, United States)
- 1983 Artificial Radioisotope Produced (S. D. D'Amico, United States)
- 1984 Artificial Radioisotope Produced (S. D. D'Amico, United States)
- 1985 Artificial Radioisotope Produced (S. D. D'Amico, United States)
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- 2020 Artificial Radioisotope Produced (S. D. D'Amico, United States)
- 2021 Artificial Radioisotope Produced (S. D. D'Amico, United States)
- 2022 Artificial Radioisotope Produced (S. D. D'Amico, United States)
- 2023 Artificial Radioisotope Produced (S. D. D'Amico, United States)
- 2024 Artificial Radioisotope Produced (S. D. D'Amico, United States)
- 2025 Artificial Radioisotope Produced (S. D. D'Amico, United States)

- 1915 *General Theory of Relativity* (A. Einstein, Germany and United States)
- 1919 *Nuclear Masses Precisely Measured* (F. W. Ashton, England)
Transmutation of Nitrogen into Fluorine by Alpha Particles from Radium Achieved (E. Rutherford, England)
- 1920 *Proton Discovered* (E. Rutherford, England)
1922. *Particle Nature of Waves Proved* (A. H. Compton, United States)
- 1925 *Wave Nature of Matter Concept* (L. deBroglie, France)
Matrix Mechanics Theory (W. Heisenberg, Germany)
1926. *Wave Mechanics Theory* (E. Schroedinger, Germany)
- 1927 *Wave Nature of Particles Proved* (C. J. Davisson and L. H. Germer, United States)
Uncertainty Principle (W. Heisenberg, Germany)
- 1928 *Quantum Mechanics Theory* (P. A. M. Dirac, England)
Quantum Mechanics Applied to Understanding of Radioactive Disintegration—Theory of Alpha Particle Emission (E. U. Condon, United States; R. W. Gurney, England, G. Gamow, Russia and United States)
1932. *Transformation of Lithium Nuclei by Artificially Accelerated Protons (Man-made "Bullets") Achieved* (J. D. Cockcroft and E. T. S. Walton, England)
Positron positively charged equivalent of the Electron, Discovered (C. D. Anderson, United States)
Neutron Discovered (J. Chadwick, England)
Deuterium D_2O (Heavy Hydrogen) Discovered (H. C. Urey, Brickwedde, and Murphy, United States)
- 1933 *Artificial Radioactivity Discovered* (I. Curie and F. Joliot, France)
- 1935 *Ordinary Uranium Discovered to have a Third Isotope of Mass 235* (A. J. Dempster, United States)
1936. *Meson Discovered* (C. Anderson, United States)
Liquid Drop Theory of the Nucleus Enunciated (N. Bohr, Denmark)
- 1939 *Nuclear Fusion of Uranium Discovered* (O. Hahn and F. Strassman, Germany)
 In March First Approach Made to Navy Department on Possibilities in Fission (Pegram and Fermi, Columbia University)
Experiment of Fermi that the Neutron Will Split U_{235} Interpreted by the Mathematical Approach (L. Meitner and O. R. Frisch, Austria)
 In July Aid of Alexander Sachs of New York Enlisted in Getting the Facts of Military Possibilities before President Roosevelt (Einstein, Wigner and Szilard)

- 1939-40 Cyclotron Developed (E. O. Lawrence, United States) Electrostatic High Voltage Atom Smasher Developed (Van de Graaff Massachusetts Institute of Technology Tuve, Carnegie Institute of Washington, Herb University of Wisconsin)
- 1940 Transuranic Elements Discovered (G. Seaborg et al., United States)
 In Summer Possible Use of Plutonium for Explosive Chain Reaction Discovered (Radiation Laboratory University of California)
 Isotope U 235 shown to be Responsible for the Fission brought about by Neutrons (Nier Booth Dunning and Von Grosse United States)
- 1940-42. Gaseous Diffusion Method of Separating Uranium Isotopes Developed (H. C. Urey and J. R. Dunning, Columbia University)
- 1940-44 Thermal Diffusion Method of Isotope Separation Investigated (R. H. Abelson, U. S. Bureau of Standard and Naval Research Laboratory)
- 1941 Centrifuge Isotope Separation Developed (Initiated by J. W. Beams, University of Virginia)
 Betatron or Electron Accelerator Developed (D. W. Kerst United States)
 In Fall Preliminary Studies of Atomic Bomb Begun (G. Breit University of Wisconsin and continued under J. R. Oppenheimer University of California)
1942. In May Delayed-Fission Neutrons Discovered (Snell Nedzel and Ibsen)
 Mass spectrographic Method of Separating Uranium Isotopes Developed (Radiation Laboratory University of California)
 December First Successful Atomic Pile Operated (E. Fermi, H. Zinn and H. L. Anderson United States)
- 1945 Atomic Bomb Developed (J. R. Oppenheimer et al., United States)
 July 16 First Experimental Bomb Dropped on Desert near Alamogordo New Mexico
 August 6 First Military Atomic Bomb Dropped on Hiroshima
 August 8 Second Military Atomic Bomb Dropped on Nagasaki
 August 10 Japan sued for peace.
- 1946 In July Atomic Bomb Tested at Bikini (U. S. Army and Navy)
- 1948 Atomic Bomb Tested at Eniwetok (U. S. Army and Navy)
 Artificial Mesons Produced (E. Gardner United States and C. M. G. Lattes Brazil)

APPENDIX B

GLOSSARY OF SOME IMPORTANT SCIENTIFIC TERMS USED IN ATOMIC ENERGY

- Absorption coefficient.** The constant μ (μ) characteristic of the nature of the radiation, its energy and of the absorbing material, for radiations whose absorption follows an exponential law
- Acceleration.** The time rate of change of velocity either in speed or direction measured by the change in unit time. Unit—one centimeter per second per second
- Accelerators.** Instruments such as cyclotrons or betatrons used to accelerate particles to a higher velocity
- Actinium.** Natural heavy element. Atomic number 89, atomic weight approximately 227
- Alpha particle** A positively charged particle emitted by certain naturally radioactive substances like uranium and radium. The alpha particle has been found to be identical with the helium atom nucleus, which consists of two protons and two neutrons. The name originally referred to the alpha radiation from naturally radioactive substances like uranium and radium, later recognized to be fast moving nuclei of ordinary helium gas
- Americium** New element, produced artificially. Atomic number 95, atomic weight approximately 241

Ampere. Unit of current of electricity. It is equal to one coulomb per second.

Angstrom. Unit of wavelength of radiation. It is equivalent to 10^{-8} centimeter or one hundred-millionth centimeter.

Atom. The smallest unit of which a chemical element is built. The simplest atoms are those of hydrogen, the most complex, those of uranium. The word is derived from the Greek and means an uncuttable thing, which makes the name rather ill adapted to an age of atom smashing and reflects the older view that atoms are fundamental, indestructible things in nature. The structure of the atom is like that of the solar system in that there is a heavy nucleus analogous to the sun with electrons rotating about it in orbits as various heavenly bodies like the earth rotate about the sun.

Atomic bomb. Although the details of the atomic bomb are military secrets, certain facts of interest have been disclosed.

Atomic bombs cannot be made smaller than a certain critical size. A small lump of uranium will not explode because it loses too many neutrons through its surface for a chain reaction to maintain itself. Before it is fired, the bomb contains the active material in two or more separated lumps too small to explode by themselves and the act of firing consists in bringing these together at a great velocity into a single lump large enough to be explosive.

Enough energy is released during the first few millionths of a second after firing to bring the material to a temperature of many millions of degrees. Thus the uranium is completely vaporized, enormous pressures develop, and expansion begins. In consequence of this expansion, the material becomes less dense, the neutrons can leak out more readily, and the chain reaction is stopped well before all the uranium is utilized.

Atomic number. (Usually denoted by Z in formulas.) This gives the number of protons (positively charged) inside the nucleus of the atom and also the number of electrons (negatively charged) outside the nucleus. Each chemical element is distinguished by a different atomic number.

All the atoms of a particular element have the same atomic

number for the chemical properties which characterize an element are determined by the number of electrons in the atom, in other words, by its atomic number. But not all atoms of the same chemical element have the same atomic weight. (See Isotope, Atomic weight, and Nucleus.)

Atomic weight. This term is used to denote the weight of any atom as measured on an arbitrary scale based on the weight of an oxygen atom. On this scale the figure 16 is chosen as the weight of the oxygen atom. Adopting this convention it is found that the weights of atoms of the other elements can be expressed very nearly as whole numbers. These whole numbers are called the rough atomic weights. The atomic weight of ordinary hydrogen is 1, that is, a hydrogen atom is roughly one-sixteenth as heavy as an oxygen atom. The atomic weight of heavy hydrogen is 2, helium, 4, lithium atoms occur in two varieties, with weights 6 and 7. The figure giving the rough weight of an atom on this scale is also the total number of protons and neutrons contained in the nucleus of the atom.

The precise atomic weights differ somewhat from these whole numbers by approximately one thousandth of the total weight. This difference, however, is of decisive importance for estimating the energy released on the formation of these atoms in accordance with the mass-energy equivalence relation.

In precise work it is important to realize that two different scales for atomic weights are in use. The physicists' scale is one in which the weight of the abundant isotopic form of oxygen is arbitrarily taken as exactly 16. The chemists' scale takes the average weight of the various kinds of oxygen atoms as they occur in nature as exactly 16. The former scale is more convenient for studies of atomic energy.

Avalanche. A process in which one electron produces more than one additional electron by collision.

Background counting rate. The background counting rate is the rate of counting caused by any agency whatever other than the radiation which it is desired to detect.

Backscattering. A process of multiple scattering of radioactive

particles from radioactive samples mounted on or near matter. This results in additional particles entering a detector. Corrections for this process may be made for each geometry used.

Barn. A unit for measuring cross sections of elements.

Beryllium. A light metallic element, but a tough one. Atomic number 4 and chemical mass 9.02.

Beta particle. A negatively charged particle emitted by certain radioactive substances. The beta particle, it has been discovered, is simply a high-speed electron having energies such as would be obtained by accelerating an electron by a potential of several million volts. While beta particles are emitted by the nucleus, it is not thought that electrons are contained in the nucleus as such. It is believed, however, that they are created (and immediately emitted) by a transformation of some of the energy in the nucleus. The processes involved in beta particle radioactivity are at present not well understood.

Beta rays. A large number of moving beta particles.

Betatron. An apparatus for accelerating electrons to give great speeds for use in nuclear bombardment experiments.

Binding energies. The energy which must be introduced into the nucleus of an atom to cause it to release a given nuclear particle (neutron, proton) or component such as an alpha particle.

Calutron. A machine for separating the various uranium isotopes based on the mass spectrograph principle.

Capture. In particular capture of a neutron by an atomic nucleus. In atomic physics this term refers to any process in which a neutron on colliding with an atomic nucleus, sticks to it or is absorbed into it, or from which fission results. Depending on the nucleus which is struck and the speed of the neutron striking it, the capture may have one of several results. For example, if a neutron is captured by a nucleus of ordinary hydrogen, some energy is given off as gamma radiation and there results a stable compound which is a nucleus of heavy hydrogen, also called a deuteron. When a neutron of any energy is captured by a U^{235} nucleus the result is the splitting of the U^{235} nucleus, i.e.,

fission. On the other hand only neutrons having energy of more than about 1,000,000 electron volts are able to produce fission when captured by U^{238} . Those of lower energy stick to the nucleus, that is, they are captured to form a nucleus of U^{239} which later through natural radioactivity transforms itself into neptunium.

Chain reaction. A term applied to any chemical or nuclear transmutation process in which some of the products of a particular change assist the further development of that change.

Specifically in the fission chain reaction used in the atomic bomb or the power producing uranium pile, the occurrence of fission is caused by the capture of a neutron by a uranium atom. Then, when fission occurs, more neutrons are released, which in turn produce fission in additional uranium atoms, and so on.

In practical devices constructed to produce chain reactions, not every neutron emitted in fission causes more fission. Indeed, except to cause an explosion a perfect chain reaction i.e., one in which every neutron causes fission, is not desirable. And in the atomic bomb designed to produce the most efficient chain reaction, some of the neutrons leak out of the surface before they cause fission. In the uranium pile some of the neutrons are absorbed by impurities or by control rods deliberately introduced to regulate the rate at which fission occurs.

The possibility of obtaining a true self maintaining chain reaction depends on the fact that more neutrons are emitted in a fission than are required to produce it. The attainment of an actual chain reaction in a practical arrangement depends on fulfilling the condition that, in spite of inevitable losses, on the average at least one of the neutrons set free by each fission is effectively utilized in producing another fission.

Charge. A quantity of electricity. The ultimate indivisible charge is the charge of one electron.

Chemical exchange. A process in which an atom in one kind of chemical substance exchanges places with a similar atom in a different substance. This exchange is influenced by the relative

masses of the two atoms of the same element, and forms the basis of methods of isotope separation and concentration

Cloud chamber Device for observing path of individual radiation particle. Track is made visible to the eye because fog droplets are formed along the path of particles

Coincidence correction Since counters have an insensitive time the observed counting must be corrected to indicate the true counting rate. This correction is sometimes called its coincidence loss correction

Control rods. Rods of neutron-absorbing material (cadmium or boron steel) used in a pile to control the chain reaction to a steady level.

Cooling A term commonly used for setting aside a highly radioactive material for some time until the radioactivity has reduced itself to a desired level

Cosmic rays Penetrating radiation, of great scientific interest, which has its origin beyond the earth

Coulomb A unit of charge. The charge on the electron is 1.60×10^{-19} coulomb (or 4.80×10^{-10} electrostatic unit)

Count. A count is a terminated discharge produced by an ionizing event in a counter tube.

Counter (Crystal) A radiation detection instrument which employs solid crystals such as silver chloride or thallium bromide.

Counter (Geiger) Instrument for detecting and counting individual radiations such as beta particles, alpha particles, and gamma rays

Counting rate voltage characteristic. The counting rate-voltage characteristic of a radiation counter tube is the counting rate as a function of operating voltage for a given constant intensity of radiation

Critical mass. The minimum amount of a given fissile material (uranium 235 or plutonium-239) required for a spontaneous chain reaction. With less than this amount, the rate of escape of neutrons through the surface of the mass is too high to result in a chain reaction

Cross section. A term used in atomic physics in measuring the

number of collisions of a given kind experienced by particles bombarding a given target. It tells the effective target area for the process in question and is thus usually expressed in square centimeters. The cross section in a bombardment of an atomic nucleus, i.e., the effective area exposed to a bombarding neutron of a certain speed, is of course, an exceedingly small quantity of the order of 10^{-25} square centimeter.

To give a familiar example, one may compare a bombardment process to shooting repeatedly at random into a large flock of ducks. The greater the average size of the ducks (the "cross section") and the greater their number in a given area, the more of them will be hit. So likewise, the number of neutrons going at a certain speed through a block of uranium which will be captured by uranium atoms varies with the capture cross section of uranium and also with the number of uranium atoms in unit volume of the metal.

Curie. Amount of activity of radon in equilibrium with 1 gram of radium. Standard measure of rate of radioactivity decay equal to 3.71×10^{10} disintegrations per second. It is equivalent to the total rate of emission of alphas from 1 gram of radium separated from its daughters.

Curium. New element artificially produced. Atomic number 96, mass numbers 240-244.

Cyclotron. A research instrument which is designed to provide a beam of high-energy protons and deuterons. It was invented in 1930 by E. O. Lawrence (University of California) and has been of great importance as a tool for research in nuclear physics.

The cyclotron involves a large electromagnet having a vacuum chamber between its poles. In this chamber an electric arc is operated at the center to act as a source of protons or deuterons. Inside the chamber are two semicircular electrodes to which is applied a radiofrequency voltage. The protons are accelerated by the electrical field between these electrodes, they then move in a semicircular path as a result of the action of the magnetic field. During the time the protons are moving around in this semicircular path the voltage on the electrodes reverses so that the

proton again is speeded up on traversing again the field between the electrodes. In this way the protons are given many successive increases in speed and acquire in the end energies of the order of several million electron volts (See Energy)

The beam of high-energy particles so produced is allowed to impinge on various materials so as to produce nuclear transformations in the atoms of these targets

Up to the beginning of the war there had been constructed about 20 large cyclotrons in various research laboratories in America, two or three in Russia and in England, one in Denmark, one in France, and three in Japan. They found extensive application in preparing artificial radioactive materials for use in medical research.

Danger coefficient. Measure of neutron-absorbing power of an impurity element in a pile.

Daughter element. The product element resulting from the spontaneous disintegration of a radioactive element.

Dead time. The time interval, after recording a count, during which the counter tube and its circuit are completely insensitive and do not detect other ionizing events (symbol t_d)

Decay curve. Graph relating decay rate (counts per minute) of a radioactive sample as ordinate versus time as abscissa.

Decontamination. Separation of undesirable radioactive substances from a desired product, e.g., separation of fission product radioactivities from plutonium

Deuterium. The special name given to heavy hydrogen, discovered in 1932 by Urey, then at Columbia University and Brickwedde, of the National Bureau of Standards. Deuterium has almost the same chemical properties as the more abundant kind of hydrogen although its atoms are twice as heavy. Heavy hydrogen makes up 1 part in 5,000 of ordinary hydrogen.

Deuteron. The special name given to the nucleus of heavy hydrogen. It is the simplest composite atomic nucleus and consists of one proton and one neutron, used as a projectile in many bombardments with the cyclotron.

Diffusate. Material which has been separated by the process of diffusion. Specifically material which has passed through a barrier in the barrier diffusion separation method for uranium isotopes.

Diffusion. The movement of molecules through a gas, liquid, or solid due to the natural motion of the molecules which is a function of their temperature. The higher the temperature, the higher the rate of diffusion.

Disintegration. The process of spontaneous nuclear change in which a beta particle, alpha particle, or occasionally a positron, is given off from the nucleus leaving the nucleus with a different atomic number.

Dyne. Unit of force. The force which will produce change of velocity of one centimeter per second in a gram mass in one second.

Efficiency of a counter gas. The ratio of particles detected by the counter to particles entering its sensitive region.

Efficiency of a radiation counter tube. The efficiency of a radiation counter tube is the probability that a count will take place when the radiation to be detected enters the effective volume of the counter tube.

Electrometer. Electrostatic instrument for measuring difference in potential. Used in radioactive research to measure change of electric potentials of charged electrodes due to ions produced by radiations.

Electron. The smallest known particle having a negative electric charge. The part of an atom outside the nucleus is made of electrons the number of which, being equal to the protons in the nucleus, is the same as the atomic number of the atom. An electric current in a wire consists of the motion of electrons through the material of the wire. A current of 1 ampere corresponds to the passage of 6.24 billion billion electrons in one second. In radio tubes and in cathode ray (television) tubes, the current is carried by a stream of electrons. The beta particles emitted by certain radioactive materials are high-speed electrons.

The mass of electrons at rest is so small that 5.02×10^{29} of

them are needed to make a pound ($10^{29} = 1$ followed by 29 zeros) The mass of all the electrons contained in a lump of matter is only about one three thousand-six hundredth of the total mass, most of the mass being contained not in the electrons, but in the atomic nuclei. An electron in rapid motion has more mass than one at rest because of the mass equivalence of its energy of motion. An electron accelerated through 512 kilovolts has twice as much mass as one at rest. Thus, the beta particles as they are emitted by radioactive materials, and the electrons in high voltage x ray tubes, may have several times their normal mass.

Electron volt. A unit of energy—the amount of energy acquired by an electron when it falls through a potential difference of 1 volt. In terms of the basic unit of energy—the erg, the relation is

$$1 \text{ electron volt} = 1.60 \times 10^{-12} \text{ erg.}^1$$

Nuclear reactions usually involve energies of the order of millions of electron volts, while chemical reactions involve energies of only a few electron volts. An electron volt is equal to the energy of a single hydrogen atom traveling at about 550 miles a minute. (See Energy.)

Electroscope. Instrument for measuring radiation by means of the ionization the latter produces in air. This ionization acting to discharge a “condenser” made of two gold leaves or of metal-coated quartz fibers.

Element. One of the basic kinds of matter—hydrogen, carbon, oxygen, uranium, etc.—from which all chemical compounds are formed (See Atom.) Each element is designated by a chemical symbol as shown in the table of elements and in the periodic chart.

Energy. Defined as the capacity for doing work. It appears in many forms, as energy of motion (kinetic energy) gravitational energy heat energy nuclear or atomic energy chemical energy and so on. But it is always measured by the work which it does. It is measured, in other words, as the product of the amount of

¹ $10^{-12} = 1$ divided by 1,000,000,000,000, i.e., 1 in the twelfth decimal place.
 $10^{-4} = 1$ divided by 10,000, etc.

force exerted multiplied by the distance through which the force acts.

$$\text{Energy} = \text{Force} \times \text{Distance}$$

For example, one unit of energy the foot pound, is the amount of energy necessary to lift a 1 pound weight a vertical distance of 1 foot.

In scientific work a great many other units are used to express quantities of energy the fundamental unit of the metric system being 1 erg. The following table gives some of the commonly used energy units, arranged in order of size, and the number of ergs contained in each

Energy unit	Equivalent in ergs
Electron volt	1.60×10^{-12}
Erg	1.00
Foot-pound	1, 36 million
Gram-calorie	41.86 million
British thermal unit (Btu)	1.05×10^{10}
Horsepower-hour	2.68×10^{13}
Kilowatthour (1, 341 horsepower hours)	3.60×10^{13}

The energy released on fission of a single uranium atom is 200 million electron volts $= 3.2 \times 10^{-4}$ erg. Therefore, to get one kilowatthour of energy it is necessary to bring about the fission of

$$\frac{3.60 \times 10^{13}}{3.2 \times 10^{-4}} = 1.12 \times 10^{17} \text{ atoms}$$

Since there are 11.6×10^3 uranium atoms in a pound, the fission of the uranium atoms in one pound of uranium brings about the release of 10.4 million kilowatthours of energy.

The total electrical energy developed in the United States in 1939 was 1.61×10^{10} kilowatthours, which is the amount of energy released by fission of

$$\begin{aligned} \frac{1.61 \times 10^{10}}{1.04 \times 10^7} &= 1.55 \times 10^3 \text{ pounds} \\ &= 775 \text{ tons of uranium} \end{aligned}$$

Enrichment factor A ratio of ratios the ratio of concentration of a given desired isotope to that of the other isotopes in the product mixture divided by the corresponding ratio in the mixture before isotope separation processes are used. Thus, to produce 90% U^{235} from natural uranium ($1/140 U^{235}$) needs an overall enrichment factor of $90/10 = 1/139$ or about 1.260

Erg Unit of work. A force of 1 dyne acting through 1 centimeter

Fissile. Capable of being split, cleavable Used to describe types of atoms such as uranium, thorium, and protoactinium which may undergo fission

Fission A particular kind of disintegration of an atomic nucleus. It is the release of energy in fission which makes the explosion in the atomic bomb Fission was first realized in late 1938 by Otto Hahn and Strassmann (German) In the fall of 1945 Otto Hahn was awarded the Nobel Prize for this discovery

In fission, the nucleus is stimulated by the capture of a neutron which strikes it. Immediately or sometimes with a slight delay the nucleus becomes unstable, breaks into two main fragments which are nuclei of elements of medium atomic weight, and spills out several neutrons

The atomic nuclei produced as fragments and the several neutrons rush apart at high speed from the point where the fission occurred The neutrons, being uncharged, move rather freely through solid matter but the nuclear fragments are quickly brought to rest by colliding against other atoms of the material in which the fission occurred

Of the elements occurring in nature, only uranium, thorium, and protoactinium are now known to be capable of undergoing fission

Fissionable. See Fissile.

Fission product. An isotope, usually radioactive, of an element in the middle of the periodic table and produced by fission of a heavy element such as uranium

Fractional distillation. Process of separation of one or more components of a mixture of substances with different boiling points

by carefully boiling off only part of the mixture. Properly done, substances may be fairly cleanly separated from each other.

Frequency In uniform circular motion or in any periodic motion the number of revolutions or cycles completed in unit time.

Gamma ray A nonmaterial short-wave radiation emitted by some radioactive atoms. It is of the same general nature as the x rays produced by a high voltage x ray tube. Gamma radiation resembles x radiation and ordinary light in being related to electromagnetic waves, but differs from other atomic radiations in that it comes from the nucleus of the atom rather than from the electrons outside the nucleus which are the source of light and x rays.

Gas amplification. The gas amplification is the ratio of the charge collected to the charge produced by the initial ionizing event.

Geiger-Muller counter A system of electrodes, usually a cylinder and concentric wire in a gas. The center wire is at a positive potential with respect to the cylinder. Under suitable conditions an ionizing event may produce ions in the gas which in turn create a uniform voltage pulse between the electrodes independent of the size of the initial ionizing event.

Geiger region. The Geiger region is the voltage interval in which the charge transferred per isolated count is independent of the charge produced by the initial ionizing event.

Geiger threshold. The Geiger threshold of a radiation counter tube is the lowest operating voltage at which the charge transferred per isolated count is substantially independent of the nature of the initial ionizing event.

Geometry factor The fraction subtended by the detector of the total solid angle as seen by the radioactive source.

Half life. The length of time it takes a sample of radioactive isotope to decrease to half of its original amount by radioactive disintegration. The number is a physical constant characteristic of the isotope, and independent of the particular amount originally present, and of external conditions such as temperature and pressure.

Half thickness. Thickness of absorbing material necessary to reduce the intensity of radiation by one half. Usually applied only when absorption obeys the exponential law

Heavy hydrogen. See Deuterium.

Heavy water Water in which all or nearly all the hydrogen is of the heavy isotope called deuterium. In ordinary water only about one part in 5,000 of the hydrogen is deuterium. The preparation of heavy water from ordinary water is an expensive separation process, mostly based on electrolysis of water by a method originated in the United States by Washburn, of the National Bureau of Standards

Since most of the weight in a water molecule is due to the oxygen, doubling the weight of the hydrogen only changes the molecular weight from 18 for ordinary water to 20 for heavy water. Since heavy water molecules are of practically the same size as ordinary water molecules, heavy water is about 10 per cent more dense than ordinary water

Heavy water is useful as a moderator in certain special forms of the uranium pile.

Helium. Second element in periodic table; nucleus is alpha particle.

Hold-up. Term used to describe the amount of valuable material tied up in processing

Initial ionizing event. An initial ionizing event is an ionizing event which initiates a count.

Integrating circuit. (a) An electronic circuit which records at any time an average value for the number of events occurring per unit time. (b) Electric circuit which records total number of ions collected in a given time.

Ion. An atom or molecule which carries an electric charge.

Ionization. The process by which an atom which is ordinarily electrically neutral acquires an electric charge. For example, in electrical discharges, as in electric arcs and neon signs, some of the atoms lose one or more of the outer electrons and are left with a net positive electric charge. Atoms can be ionized by absorption

of light or absorption of x rays or as a result of being struck by an electron. An atom thus ionized is called an ion.

Ionization chamber. Instrument for measuring directly the amount of ionization radioactivity produces in air or other gas. A volume of gas in which a field exists due to a system of charged electrodes. Ions produced in the gas by an ionizing event are collected at these electrodes. The ion current is a measure of the character and intensity of the radiations.

Ionizing event. An ionizing event is any event in which an ion is produced.

Isobars. In nuclear science, two atoms with different atomic number but with the same mass number. For example, cadmium 113 and indium 113, neptunium-239 and plutonium 239.

Isotope. A species of an element in which the atoms are of uniform atomic weight. Atoms of a given element which have different numbers of neutrons in the nucleus and therefore differ in mass or weight.

Most chemical elements occur as a mixture of several isotopes, i.e., as a mixture of atoms which are alike in chemical properties but fall into several groups according to weight. For example, chlorine is a mixture of two kinds of chlorine atoms having rough atomic weights of 35 and 37. Uranium occurring in nature is a mixture of U^{235} (also written U^{235}) an isotope with weight 235, U^{238} an isotope with weight 238, and a very minute amount of an isotope with weight 234. In the symbol designating a particular isotope, the rough atomic weight is usually written in the symbol thus C^{12} , C^{13} , U^{235} , U^{238} (See also Atom and Nucleus).

Isotope separation methods. (Used in separating U^{235} from U^{238} .) Because isotopes of the same element have almost identical physical properties and identical chemical properties, the problem of separating them from one another is extremely difficult. Several methods developed in the laboratory before the war were extended to full-scale factory production to obtain uranium for the atomic bomb project. All the plants so developed were constructed at Oak Ridge, Tenn.

(a) Mass-spectrograph method In this method the material, some volatile compound of uranium, is passed as a vapor into an electric arc in a vacuum tank. This ionizes the uranium atoms (leaves them positively charged by knocking off one or more of the neutralizing electrons outside the nucleus) The ionized atoms (called ions) are then accelerated by application of high voltage. The whole tank is placed between the poles of a large electromagnet which causes the ions to move in circular paths, the radii of which depend on the mass of the ions. The ions of two isotopes of uranium, U^{235} and U^{238} move in paths of slightly different radii and so can be collected in separate containers.

For the atomic bomb project this method was developed at the University of California.

(b) Diffusion method depends on the fact that when a mixture of gases is allowed to diffuse through a membrane, the molecules of lighter weight get through more rapidly than the heavy ones, resulting in a partial separation of the mixture. Actually when the gases are as similar in weight, as volatile compounds containing the two isotopes of uranium, the degree of separation attained by one passage through a membrane is exceedingly minute. In order to achieve a useful degree of separation it is necessary to arrange for the gas to be diffused successively through many hundreds of membranes.

The research for this method was carried on in New York City at Columbia University.

(c) Thermal diffusion method depends on the fact that when a gaseous or liquid mixture is maintained under conditions where one part of it is hot and another cold, there is a partial separation of the mixture, with the differences in composition corresponding to the differences in temperature. This is also a very minute effect and arrangements must be made to augment the effect by repetition of the process.

Isotron Device for electromagnetic separation of isotopes in which the ion source is of large area, rather than a slit as in the usual mass spectrograph.

Joule. Unit of work equal to 10^{-7} ergs

Lattice. The geometrical arrangement of the uranium or plutonium rods in a pile.

Length of a plateau. The length of the plateau is measured from the Geiger threshold to the voltage at which the slope deviates appreciably from a straight line.

Linear accelerator A high-voltage machine used for accelerating particles. It is similar to the cyclotron except that the particles are accelerated in a straight line by the repeated application of voltage to a number of electrodes through which the particle passes.

Linear amplifier An electronic amplifier whose gain is constant for a wide variation of amplitude of input signal. Hence, the output signal may vary linearly with the input signal.

Magnetron. Apparatus for electromagnetic separation of uranium isotopes (not actually used in U ²³⁵ production)

Mass. The quantity of matter effectively the same in weight.

Mass-energy equivalence. This fundamental proposition, enunciated by Einstein in 1905 as one of the important practical consequences of the theory of relativity states that when anything gives off energy it also loses weight or mass.

By the formula given by Einstein for this equivalence, the complete destruction of 1 pound of mass would be accompanied by the release of 10.66 billion kilowatthours of energy. (In the units used in pure physics the destruction of 1 gram of mass is equivalent to the release of 9×10^9 ergs of energy.) The size of this figure can be seen by comparison with the total electric power production in the United States which, in 1944, amounted to a little over 279 billion kilowatthours, the equivalent in mass, according to this formula, of .6 pounds.

This law is presumably true in all cases but in the ordinary burning of a fuel the loss in mass is too small to be observed. In the releases of atomic energy produced thus far which are millions of times greater for the mass of materials involved than in

ordinary fuel combustion it must be remembered that less than 1 per cent of the total mass of material involved is actually consumed

Mass number This is another term for the rough atomic weight; approximately the weight of the nucleus. It tells the total number of protons and neutrons in the nucleus. It should not be confused with atomic number which gives at once the number of protons in the nucleus and the number of electrons outside the nucleus

Mass spectrograph. Instrument for sorting out and registering the masses of atoms and light molecules. This is made possible because the path of an ion in a magnetic field is curved. Particles of different masses travel curved paths of slightly different radii.

Meson (or Mesatron) An intermediate particle of about 200 electron masses and a half life of 2.1×10^{-6} found either positively or negatively charged

Mev Million electron volts

Micro Prefix meaning one millionth

Milli. Prefix meaning one thousandth

Moderator This is the name given to any material used for the purpose of slowing down the average speed of a group of neutrons by means of impacts of the neutrons with the atomic nuclei in the material of the moderator. It is essential that the nuclei of the atoms in the moderator do not absorb or capture the neutrons but merely act as buffers to slow them down and absorb part of their energy. The moderator is an important constituent of the energy and plutonium producing uranium pile. Thus far graphite has been used most frequently although it must be specially manufactured to avoid contamination by certain elements, especially boron, which strongly absorb neutrons. Since the neutrons lose energy by elastic impacts with the nuclei in the moderator it is desirable to have a material of low atomic weight. Because ordinary hydrogen absorbs too many neutrons, ordinary water is ineffective. Heavy hydrogen (deuterium) in the form of heavy water is good although its extraction from ordinary water is an expensive process. Metallic beryllium is also a suitable moderator

Molecule. A chemically distinct grouping of atoms which cannot be further broken down without changing its nature, e g., H_2O (water) $\text{C}_2\text{H}_5\text{OH}$ (alcohol) C_6H_6 (benzene) $\text{C}_6\text{H}_{12}\text{O}_6$ (grape sugar) $\text{C}_6\text{H}_2(\text{NO})_3$ (TNT)

Multiplication factor The number of neutrons produced for every neutron disappearing in a chain reaction system (pile) If the factor is equal to one, or greater the chain reaction proceeds Where the factor is less than one, the chain reaction cannot maintain itself

Neptunium. A new chemical element not occurring in nature, whose atomic number is 93 and atomic weight is 239

It is produced in the uranium pile as an element intermediate in the process of making plutonium When a U^{238} atom in the pile captures a neutron, it becomes U^{239} which is radioactive, emits a beta particle, and is thus transformed into Np^{239} This kind of neptunium is also radioactive and emits another beta particle whereby it is transformed into Pu^{239} plutonium, the fissionable material used in making atomic bombs

Neptunium, like plutonium, was discovered by Segre, Seaborg, Kennedy and Wahl, at Berkeley Calif., in 1940

Neutron. A particle with no electric charge, but with a mass approximately the same as that of the proton, about 1.67×10^{-24} gram In nature, neutrons are locked up in the nucleus of an atom, but they can be knocked out in various kinds of atom smashing experiments The number of neutrons in a particular nucleus is found by subtracting the atomic number from the rough atomic weight.

Neutrons were discovered in 1932 by Chadwick (British) He obtained them in a free state by bombarding beryllium atoms with alpha particles from radium. This knocked the neutrons out of the beryllium nuclei and is still a useful laboratory way of producing streams of free neutrons of low intensity

Neutrons play an especially important role in the practical utilization of atomic energy because when a uranium atom undergoes fission through the capture of a neutron, several more neu-

trons are produced which continue the process by the mechanism of a chain reaction

Because they are electrically neutral, neutrons can move rather freely through most solid materials. They are, however, scattered by impact with the nuclei so that they move through matter by diffusion rather than by direct forward motion. Likewise, they are absorbed to some extent, the free neutrons being captured by nuclei to form new isotopic atoms which are in some cases radioactive.

The ability of nuclei thus to capture neutrons varies enormously from one atomic species to another and depends very greatly on the speed of the neutrons. Some substances are almost transparent to neutrons, others almost "opaque." There is no known substance which will act like a wall for neutrons and bounce back all the neutrons that strike it in the way that a steel boiler wall bounces back the molecules of steam that strike it.

Non-self-quenching counter tube. A counter tube which requires the use of a quenching circuit to terminate the discharge.

Normalized plateau slope. The normalized plateau slope is the slope of the substantially straight portion of the counting rate voltage characteristic expressed as a ratio of the percentage change in counting rate near the midpoint of the plateau to the percentage change in operating voltage.

Nucleus. The central part of the atom, which makes up most of the weight of the atom and is charged with positive electricity. Atomic nuclei are, it is now believed, made up of two kinds of fundamental particles: protons and neutrons.

The total number of particles of both kinds in the nucleus is given by the rough atomic weight. The number of protons is given by the atomic number. The number of neutrons can thus be found by subtracting the atomic number from the atomic weight. For example, in uranium-238 the total number of protons and neutrons is 238. The number of protons alone, given by the atomic number of uranium, is 92. Hence, by subtraction, the number of neutrons is $238 - 92 = 146$.

In the atoms of certain elements the nuclei, although all having

the same number of protons i.e., the same atomic number differ as to atomic weight (see Isotopes) For example, most hydrogen atoms have a single proton for a nucleus Consequently hydrogen is said to have an atomic weight of 1 But there are hydrogen atoms with a nucleus compounded of one proton and one neutron. These heavier atoms can be separated from the lighter more normal hydrogen atoms to make heavy hydrogen (deuterium) a material with the same chemical properties as hydrogen, but with a rough atomic weight of 2 Some elements are represented by atoms of many different weights Every atom of mercury for instance, has 80 protons in its nucleus, but with respect to atomic weight, it may fall into any one of seven different varieties having the rough weights 196, 198, 199, 200, 201, 202, and 204.

At the time progress in fundamental science was interrupted by the war the basic problem was to learn the nature of the forces which hold together the particles in the nucleus Evidently forces of a new kind must play a role here for the neutrons, being neutral, are not affected by electric charges, and the protons, being all positively charged, would fly apart if their mutual electrical repulsions were not overcome by some special nuclear attractions The nature of these forces is as yet not fully known

Ohm. Unit of electrical resistance

Operating voltage. The operating voltage of a radiation counter tube is the voltage across the tube in the quiescent state

Overshooting. A counter is said to overshoot if the change in voltage of the anode is greater than the overvoltage.

Overvoltage. The overvoltage of a radiation counter tube is the difference between the operating voltage and the Geiger threshold

Periodic table. An arrangement of the chemical elements, first made by Mendeleeff (Russian) to show resemblances among them with respect to their chemical properties

In this table the elements are arranged in rows by order of atomic number When this arrangement is made, it is found that the elements in certain groups and in certain vertical columns of

the table are those exhibiting similar chemical properties. For example, elements in the right-hand column of the table—helium, neon, argon etc.—are all inert gases

The reason for this periodic recurrence of similar chemical properties in the elements arranged in this way is given by the theory of the electronic structure of the atom developed by Bohr (Danish) and perfected by Pauli (Austrian). For his contribution to this work, Pauli, now at the Institute for Advanced Study in Princeton, N. J., was awarded the Nobel Prize in physics in November 1945.

Pile. This term refers to the particular arrangement used to produce a chain reaction with uranium for the purpose of producing plutonium or for getting heat energy for generation of power. The Atomic Energy Commission has adopted "reactor" as a preferred term for "pile."

The original pile was built on the campus of the University of Chicago and first operated on December 2, 1942. It consisted of blocks of graphite interspersed with lumps of metallic uranium, the whole being roughly in the shape of a sphere containing 12,400 pounds of uranium metal.

Subsequently several other piles were built for special purposes prior to the construction of the large plutonium production plant at Hanford, Wash.

The underlying idea of the pile may be explained simply. The neutrons released in fission have such high speeds that they are not very effectively captured again to produce further fissions and to carry on the chain reaction. Only neutrons at very low speeds will produce fission; those with high energy tend to pass right through the nuclear targets at which they are aimed without splitting them. To reduce the speed of the neutrons it is necessary for them to diffuse in some material of low atomic weight where they will lose energy by elastic impacts with the atoms of this material.

In the pile this moderator material is kept in layers or lumps separate from the uranium. This is necessary because uranium has a strong tendency to absorb neutrons of medium speed in

a way that does not result in fission. The neutrons which become effective are those which are slowed below this speed in the moderator and diffuse back into the uranium to produce more fission.

Since their primary object was plutonium production and not heat, the piles that have been built thus far have been kept at relatively low temperatures either by dry air cooling or by water cooling pipes. For power production it will be necessary to work out engineering designs which permit the piles to operate at a high temperature to generate steam for use in steam turbines driving electric generators.

The details of pile design will vary greatly depending on the primary purpose of the pile, the moderator material which is chosen, and depending on whether natural uranium or uranium with enriched U^{235} content is used. In operation a pile becomes enormously radioactive, so that all work connected with it must be done by remote control, behind very thick absorbing walls to avoid dangerous burns to the operating personnel. The whole future of the peacetime use of atomic energy depends on the success with which piles can be developed for various special purposes.

Plateau. The plateau is the approximately horizontal portion of the counting rate voltage characteristic of a radiation counter tube.

Plutonium. A new chemical element not occurring in nature, whose atomic number is 94. It was discovered by Segre, Seaborg, Kennedy and Wahl working at Berkeley Calif., in 1940. Plutonium (symbol Pu^{239}) is used in making atomic bombs, the large plant at Hanford, Wash., having been designed solely for its production. This highly radioactive element is formed as a result of two successive beta particle transformations from U^{239} which itself is produced in the uranium pile. (See Neptunium.) The isotope Pu^{239} is an atomic explosive like U^{235} .

Polonium. A radioactive element of atomic number 84 and approximate chemical mass 210 named by Madame Curie, its discoverer.

Positron Positive electron, appears in certain decays of radioactive substances and in cosmic radiation.

Power A distinction should be made between power and energy. Power differs from energy in that it brings in the element of time. The faster a given amount of work is to be done, the more power is required. The amount of energy required is the same, regardless of the time in which the work is done.

The simplest direct unit of power is the foot pound per second, which is the amount of power needed to lift a weight of 1 pound vertically at a speed of 1 foot per second. The most familiar electrical power unit is the kilowatt.

The relations between the common power units are as follows

Unit	Number of foot pounds per second
Watt	0.73756
Horsepower	550
Kilowatt (1,000 watts)	737.56

It is important to recognize distinctly the difference between a kilowatt of power and a kilowatthour of energy. A kilowatthour measures the work done by a device delivering a kilowatt of power for 1 hour. To say that the installed capacity of a power generating station is 40,000 kilowatts is to say that it can deliver energy continuously at that rate, and does not give the total amount of energy delivered in any given period of time.

Since 1 pound of uranium undergoing fission releases 10.4 million kilowatthours of energy it follows that the utilization of 10 tons per year of uranium would provide a steady output of power of

$$\frac{10 \times 2000 \times 10.4 \times 10^6}{365 \times 24} = 23.7 \text{ million kilowatts}$$

Predissociation. A process by which a complex molecule will lose energy by dissociation before it has had an opportunity to radiate.

Proportional counter A system of electrodes in a gas in which the

number of ions produced in the gas produces a pulse which is proportional to the number of ions produced in the gas by the primary ionizing particle.

Proportional region. The proportional region is the voltage interval in which the gas amplification is greater than 1 and in which the charge collected is proportional to the charge produced by the initial ionizing event.

Protoactinium. A heavy element of atomic number 91 atomic weight 231 capable of undergoing fission on neutron capture. This element is extremely rare and for this reason will probably not find practical application in atomic energy developments

Proton. A small particle with a positive electric charge equal numerically to the negative electric charge of the electron, 1.60×10^{-19} coulomb. A single proton makes up the entire nucleus of the ordinary hydrogen atom. The nuclei of atoms of other substances contain a number of protons given by the atomic number of the element. The mass of the proton is so small that it takes 2.72×10^{26} of them to make 1 pound. The mass of the proton is, however, 1,840 times greater than that of the electron.

Quantum. A discrete particle of energy (according to Planck)

Quenching. The process of terminating the discharge in a counter tube.

Quenching circuit. A circuit which causes the discharge to cease.

Quenching vapor. Polyatomic gas used in Geiger Muller counter to "quench" or extinguish a pulse thus eliminating need for external quenching resistor or electronic circuit. The quenching action of vapor is due to the fact that it absorbs ultraviolet photons emitted by excited atoms and prevents emission of secondary electrons when ions reach the cathode.

Radiation. Particles, x rays, gamma rays, or light moving between or past atoms, and not part of their stable structure. Radiation consists of any electromagnetic quantum or any moving electron or nuclear particle charged or uncharged

Radioactive equilibrium. The state which prevails when the

amount of a radioactive isotope stays constant because new atoms are being formed at the same rate at which they disintegrate through radioactive decay

Radioactivity A property of certain elements which causes their atomic nuclei spontaneously to disintegrate, gradually transmuting the original elements into others of different chemical properties. The radioactive atomic species occurring in nature include all elements whose atomic number is greater than that of lead. Since 1930, physicists have succeeded in transmuting nearly all the chemical elements into radioactive forms by artificial bombardments. Many such materials are also produced as fission products.

The radiations emitted by radioactive materials have proved very useful in the study and treatment of cancer and other tumorous diseases, and in medical diagnosis and therapy generally. Rapid developments in this field may be expected now that abundant supplies of radioactive materials can be provided by uranium piles.

The rate at which radioactive materials transform is measured by time intervals, called the half life; in the first half life, the amount of material left unchanged is half the original amount; in the next half life interval, half the remaining amount, or one-fourth the original amount, remains. The half life of different materials varies widely: for uranium-238 it is 4.67 billion years; for radium it is 1 690 years; for polonium-210 it is 136 days, while for a special isotope of polonium (214) the half life is only about a millionth of a second.

The radiations emitted by radioactive materials are of three types, alpha particles, beta particles, and gamma rays. When an alpha particle is emitted from the nucleus of an atom, the atomic weight is diminished by 4 and its atomic number by 2. For example, when U^{238} emits an alpha particle, the remaining nucleus becomes an isotope of thorium, Th^{234} . When a beta particle is emitted the atomic number is increased by 1, since the beta particle carries away a negative electric charge, but the rough atomic weight is unchanged because the mass of an electron is so small.

- Thus, the thorium isotope Th^{234} produced from U^{238} is itself radioactive, emits a beta particle and becomes Pa^{234} an isotope of protoactinium. Emission of gamma radiation by an element does not change its atomic number or atomic weight but occurs in close association with the emission of alpha or beta particles.
- Radium.** A radioactive element. Atomic number 88, atomic weight 226.05
- Radon.** A radioactive gas, an element with atomic number 86, and chemical mass 222
- Rate meter** See Integrating circuit (2)
- Reactor** "Reactor" has been adopted by the Atomic Energy Commission as a preferred term for a "pile."
- Recovery time.** The time interval, after recording a count, before the pulses produced by the next ionizing event in the counter are of substantially full size
- Region of limited proportionality** The region of limited proportionality is the voltage interval below the Geiger threshold in which the gas amplification depends upon the number of ions produced by the initial ionizing event and also on the operating voltage.
- Relative plateau slope.** The relative plateau slope is the average slope of the plateau expressed as the percentage change in the counting rate near the midpoint of the plateau per 100 volts change in the operating voltage
- Reproduction factor** Same as multiplication factor
- Resolving time.** The minimum time interval between counts that can be detected. Resolving time may refer to an electronic circuit, to a mechanical recording device, or to a counter tube
- Resonance energy** Particular energy of bombarding particle for which nucleus is exceptionally reactive.
- Röntgen (R)** That quantity of radiation which produces one electrostatic unit of electricity of either sign per cubic centimeter of air at standard pressure and temperature.
- Röntgen rays** Commonly known as x rays
- Rutherford.** 10^6 disintegration per second

Scaling circuit or scaler An electronic circuit capable of dividing the incoming pulse rate by a constant factor so that mechanical methods for recording the pulse may be used

Self-absorption. Absorption of radiations by the source material itself

Self-quenching counter tube. A counter tube in which the discharge ceases due to an internal mechanism within a counter tube.

Separation factor Same as enrichment factor

Slow neutrons. Neutrons which have been bounced about in a large block of paraffin or water and have lost most of their energy When their velocities are comparable to that of hydrogen atoms in paraffin or water the neutrons are called slow neutrons

Spurious counts. Spurious counts are counts caused by any agency whatever other than radiation

Starting potential. Starting potential for a pulse type ionization chamber the lowest amplification for which pulses will be registered by the detecting circuit.

Starting voltage. The minimum voltage which must be applied to a counter tube to cause it to count, with the particular recording circuit which may be attached (symbol V)

Statistical time lag. The time between the occurrence of the primary ionizing event and the occurrence of the count in the counter tube

Supply voltage. The voltage which must be supplied to the counter circuit in a counter tube, and a quenching circuit, if any (symbol V_s)

Thermal diffusion Method of separation of uranium isotopes depending upon higher rate of movement at given temperature for light particles

Thermal utilization factor Fraction of slow neutrons in pile absorbed by the uranium in the pile rather than by the moderator, impurities, fission products, etc.

Thorium. A heavy element of atomic number 90, and chemical mass 232.12, which is capable of undergoing fission on capture

of a fast neutron. Thorium has thus far not found application in atomic power production

Tracer A radioactive isotope used in experiments and so called because it can be traced through the various chemical or biological processes

Transmutation. The process of changing an atomic nucleus to one of different atomic number or atomic weight by bombardment with nuclear particles from the outside, as in a cyclotron or pile.

Transuranic elements. Elements with atomic numbers higher than that of uranium (number 92) For example, neptunium (93) plutonium (94)

Tritium. An artificially produced radioisotope of hydrogen, approximately three times as heavy as the ordinary hydrogen atom

Uranium The critical element that is used in the atomic bomb and in atomic power production because of the ability of its atoms to undergo fission when it absorbs neutrons

Uranium has an atomic number of 92 and consists mostly of two isotopes of rough atomic weights 238 and 235. The U^{238} makes up 99.3 per cent and the U^{235} about 0.7 per cent of the natural metal. Minute amounts of U^{234} are also found in natural uranium.

Uranium was discovered in the year 1789 as an element occurring in the mineral pitchblende. It was not prepared in metallic form until 1841. The discovery of its natural radioactivity was made in 1896 by Henri Becquerel and a few years later the much more intense radioactivity of radium was discovered by Pierre and Marie Curie.

Since radium always occurs in nature in association with uranium bearing minerals, most prospecting for uranium heretofore has been for the primary purpose of finding radium. Some uranium has been used in certain alloy steels; also uranium compounds find application as pigments in the ceramic and glass industries. It was used in amber signal lenses and in glass of special coefficient of expansion for glass-to-metal contacts in radio tubes.

Prior to the discovery of fission, however, no very important uses for uranium had been discovered.

Uranium ores. Although uranium is contained in over one hundred minerals, only two—pitchblende and carnotite—are of great importance. It is estimated that uranium is present in the earth's crust in the proportion of about four parts per million. Early rough estimates were that the nuclear energy available in known world deposits of uranium is adequate to supply the total power needs of this country for 200 years (assuming utilization of U^{235} as well as U^{238}).

Pitchblende is found in metalliferous veins, notably in Bohemia and Saxony. The most important uranium mineral deposits are in Jachymov in Czechoslovakia, in Colorado, in the Belgian Congo and at Great Bear Lake in Canada. There are also important deposits in Tjuma-Mujun, Ferghana, East Turkestan, a region belonging to the Union of Soviet Socialist Republics. In 1923, it was estimated that the uranium content of these deposits amounts to 60 tons. Other deposits, widely distributed throughout the world, are not rich enough to be worked at present in competition with the main deposits.

In most minerals there are 2.8 million grams of uranium for every gram of radium.

In the mines of Czechoslovakia and also of the Belgian Congo the average yield of radium is about 0.1 gram radium per (metric) ton of ore.

Most of the importations to this country during 1942 and 1943, the last years for which importation figures are available, were from Canada and the Belgian Congo.

Pitchblende of good quality contains as much as 80 per cent of uranoso-uranic oxide (U_2O_5). It is a brown to black ore with pitch like luster in the form of crystallized uraninite.

Carnotite, the second main source of uranium, has been discovered in Arizona, Colorado, and Utah. It is found as a canary-yellow impregnation in sandstone. Production of this ore climbed steadily during the middle thirties from 54 short tons in 1934 to a high of 6256 in 1939. The
ds of ura

extracted from the ore produced in 1939 were 59,269 The actual extent of deposits has not been divulged.

Volt. Unit of electromotive force, which causes the flow of electric current.

Voltage pulse. A change in volts of the central electrode system of the counter tube.

Wavelength. The distance between the top of one wave and the top of the next succeeding one.

Work. Force times distance The unit of work is the erg.

X rays. Invisible, penetrating, high-frequency light rays

Yield. The ratio of the observed counting rate of a radioactive sample to its disintegration rate.

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APPENDIX C

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Discovery 194

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Electrical Engineering 82 83 110 173 177

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Electronics 117 308

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Engineer The 164

Engineering Journal 203

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Farm Research 261

Financial World 183

Fire Engineering 155

Fortune Magazine 71 84 135

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Industrial Medicine 209 215 217

Industry and Power 24, 186

Investors Reader 154

Iron Age, The 102 114 199 301 305

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Bibliography

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 Pegasus, The 156
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 Power Generation 160 183
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 Public Affairs 4
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 Sunday Night 138

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 28 36 38 44, 48 56 75 105 126 129 139 143 148 151 152
 204, 207 216 227 247 251 255 259 274 278 279 280 289, 315

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 Westinghouse Engineer 120 200 299
 Whaley-Eaton Service American Letter 163

INDEX

INDEX

- Absorption, rate of, 177
 Absorption coefficient, 193
 Acceleration, 193
 Accelerators, 193
 linear 109
 Actinium, 193
 Added corners, 180
 Agriculture, Department of, 133
 Air as coolant, 8
 Aircraft, 3, 6, 15, 50, 112 113
 atomic engines, 112-122, closed
 cycle turbine, 113-114, heat
 transfer problem, 117-118, ram
 jet, 115-116 129; rocket, 116-
 11, 129 shielded problem,
 118-122 turbo jet, 114-115,
 129
 Alfalfa, 144
 Alkali cellulose, 92
 Alpha emitters, 99
 Alpha keto glutamic acid, 156
 Alpha particles, 31-32 39, 40, 59-60
 61 64, 68, 81
 defined, 193
 Alpha tricalcium phosphate, 142
 Alumina, 103, 129
 Aluminum, 79-80
 Americium, 53
 defined, 193
 Ammon acids, 148, 152 155 156, 171
 Ammoniated superphosphate, 142
 Ampere, 104
 Amplifier, linear, 109
 Anderson, Carl, 36
 Anemia, 150
 Angstrom unit, 194
 Anions, 150
 Antibiotics, radioactive, 181
 Antimony 54
 Antitetanus serum, radioactive, 56
 Antitoxins, 178
 Area measurement, radioactive, 67 68
 Aroostook County Maine, 142
 Astatine, 53
 Atom defined, 194
 history of research, 7-46
 Atomic bomb energy etc., see Bomb
 Energy etc.
 Atomic Energy Commission, 73 n
 86 n 88 90 134 144
 Austenite-pearlite reaction, 105 109-
 110
 Automobiles 15 119
 Avalanche, 19,

 Background counting rate, 19,
 Backscattering defined, 195-196
 gamma ray 94-96
 Bacteria radioactive, 56
 Balance, radioactive, 70
 Barn defined, 196
 Baruch, Bernard M. 86 n.
 Beam method, atomic, 104-105
 Becquerel, Henry 30-31
 Beltsville, Md 135 140
 Beryllium, 14 39, 42, 51 77 160
 defined, 196
 oxide of 126
 Beta emitters, 99
 Beta particles, 31-32, 39 41 54, 66
 6-68, 81 110, 147
 defined, 196

- Betatron, 39
 defined, 196
 Binary diffusion (solid metals) 105-
 106 107-108
 Binder technique, 129-130
 Binding energy 37
 defined, 196
 Biochemical analysis, 150-154, 171-
 172
 Biology radioactive tracers in, 145-
 158
 procedure, 149-150
 table of isotopes, 148
 use, in biochemical analysis, 150-
 154 in intermediary metabolism,
 154-158
 Birchenall, C. E., 105 n.
 Blood counts, 110
 Blood serum, 150
 Bohr Niels, 33
 Bomb atomic, 1-2, 5 11 16 18 24,
 26, 44-46
 and ceramics, 123-128
 countermeasures, 6-7
 defined, 194
 international control, 4
 Military Commission, 8-11
 Bonhoeffer 146
 Boron 39 42 77 80 85 107
 radioactive, 136
 Breast, cancer of 171
 Brookhaven National Laboratory
 N. Y., 82, 87
 Buerger M. J., 130
 Bureau of Plant Industry Soils and
 Agricultural Engineering, 134

 Cadmium, 85
 Calcium 103-104 144
 radioactive, 103 136-137 143-144,
 150
 Calcium deoxidation constant, 102
 Calcium metaphosphate, 142
 Calcium sulfate, 179
 California, University of 126, 208
 Calutron, 196
 Canada, 4, 7 ff

 Canadian Radium and Uranium
 Corp 133-134
 Cancer 41 170-171 184
 See also Leukemia, names of
 various organs
 Canning of nuclear fuel, 83
 Capture, 196-197
 Carbohydrate metabolism, 157
 Carbon 14 77 103
 radioactive, 55-57 107 136, 147-
 148 157 184-185
 Carbon dioxide, 157 184-185
 radioactive, 178
 Carbon disulfide, 92, 93 98
 Carbon-silicon carbide couple, 104
 Carboxyl, 148
 Carbon nitro loam, 143
 Carnegie Institute of Technology
 Metals Research Laboratory
 101-111
 Cathode rays, 28, 30
 Cathodes, radioactive, 66
 Cells, 150
 Cellulose, 92
 Cellulose xanthate, 92, 93-94, 95, 98
 Ceramics, and development of atomic
 bomb, 123-128
 research trends, 128-131
 Cerium, sulfide of 126
 Chadwick, James, 34
 Chain reaction 12-14, 44
 byproducts, 51-57
 defined, 197
 See also Radioactivity
 Chapman, 162
 Charge, 197
 Chemical exchange, 197-198
 Chemical process control, 89-100
 problems involved, 99-100
 rayon industry 91-93 dyeing proc-
 ess control, 97-98, liquid level
 gauge, 96-97 safety devices, 93-
 94, specific gravity measurement,
 94-96, tracing reactions, 98-99
 Chemistry and radioactivity 54-55
 179-180
 Chicago University of 1 n.
 China 8

Index

- Chlorine, radioactive, 136, 137 150
 Cholesterol, 156
 Chromatographic absorption 180
 Chromium, 107
 Current, integrating, 206
 quenching, 217
 scaling, 20
 Circulation, studies of, 150
 Clay (kaolinite) 125 127 128 130
 Closed-cycle turbine, 113-114
 Cloud chamber, 198
 Coal, 15 17 49 85
 Cobalt, 54, 107
 Coincidence correction 198
 Colloids, 180
 Columbia University 208
 Communism, 22
 Compounds, 27
 Compton, Arthur H., 124 n
 Concrete, 81 122
 Control rods, 84-85
 defined, 198
 Coolants, 13-14, 8 80, 8 -83 84
 Cooling, 198
 Cooperation, need of 18-20
 Copper 107
 Coprecipitation, 150
 Corn, 137-138 141-14
 Cornell University 143-144
 Corrosion detection with radioactivity
 96
 Cosmic rays, 52, 81
 defined, 198
 Cotton, 138-139 141-142
 Coulomb, 198
 Count, 198
 Counter (crystal) 198
 See also Geiger Muller counter
 Counter gas, efficiency of 201
 Counting rate voltage characteristic,
 198
 Cousins, Norman, 18
 Critical mass, 74-75
 defined, 198
 Crookes, Sir William, 28 29
 Cross section, 198-199
 Crystal counter 198
 Cu-Ni-Zn system, 106 108
 Cune, Marie and Pierre, 31
 Cune defined, 199
 Cunum, 53
 defined, 199
 Cyclotron, 13 39 40, 55 1 6 173-
 174
 defined, 199-200
 Cystathionine, 154
 Cystine, 153-154

 Dalton John 7-28 -9
 Danger coefficient, 200
 Daughter element, 00
 Davidson clay loam, 143
 Dead time, 00
 Decay curve, 200
 Decontamination, 110
 defined, 00
 Democritus, 7
 Deuterium (heavy hydrogen) 39 77
 146 148 155-156, 157
 defined, 200
 Deuteron, 39 40 42
 defined, 00
 Dicalcium phosphate, 14
 Diffusate 01
 Diffusion, 201
 thermal, 0
 Diffusion measurements, metallurgy
 105-108
 Disarmament, atomic, 10
 Disintegration, 201
 rate of 1-7
 Distillation, fractional, 04-05
 Drugs, 178 181
 duPont de Nemours E. I. & Co 52
 du Vigneaud, Vincent, 154
 Dyeing process control, 97-98
 Dyne, 201

 Eastman, E. D. 126 n
 Edison, Thomas A. 19
 Education, need of, 0-21
 Efficiency of counter gas, 201
 of radiation counter tube, 201
 Einstein, Albert, 37 209

- Electricity 28-29
 generation by atomic power 13,
 49-50
 Electrometer 201
 Electron volts, 37-38 40 43-44
 defined, 202
 Electrons, 28-30 32-36, 39 43
 defined, 201-202
 Electroscopes, 202
 Electrostatic voltmeter radioactive,
 63-64
 Elements, 27
 defined, 202
 plant food, 136
 radioactive, *see* Radioisotopes
 transuranic, 53 221
 Elutron, 180
 Energy 202-203
 atomic, and war *see* Bomb, atomic
 for aircraft, *see* Aircraft
 history 27-46, 189-191
 peacetime uses, 7 ff., 11-18, 47-51
 social implications, 18-25
 Enrichment factor 204
 Enteric coated pills, 177
 Erg, 204
 Ethyl alcohol, 178
 Ethylodide, 160
 Evans, 162
 Exchangers, heat, *see* Heat exchangers
 Excretion products, 157
- Faraday Michael, 18-19
 Fast reactors, 76-77
 Fat metabolism, 155-156
 Fe C B system 106
 Fe Si C system 106
 Federal Food, Drug, and Cosmetic
 Act, 174
 Feldspar 128 130
 Fermi, Enrico 42
 Fertility soil, 138-140
 Fertilizers, *see* Soil fertilizer research
 Fever I 65 n., 69 n., 70 n.
 Films, radioactive scanning device,
 67-68
- Fluile, 204
 Fusion, nuclear 12-14, 43-44, 74,
 124-125
 defined, 204
 Fission product, 204
 Flint, 128 130
 Foote, Dr., 163
 Fractional distillation, 204-205
 France, 4, 8
 Francium, 53
 Frequency 205
 Friedrich, 183
 Fuels, nuclear 75-76
 canning of, 83
- Gage, liquid level, radioactive, 96-97
 Galvanometer radioactive, 69-70
 Gamma ray emitter 94-99
 Gamma rays, 31 45 54, 66, 69, 80-81,
 120-121 147 151
 defined, 205
 Gas amplification, 205
 Gases as coolants, 82-83
 Geiger Muller counter 92-97 103,
 147 151 164
 defined, 205
 Geometry factor 205
 Germany 22 129
 Glycine, 152
 Glycogen, 157
 Gold-silver system 105-106, 108
 Goldstein L., 63 n. 64 n.
 Government, world, 2-3, 24
 Gram boundary 108
 Graphite, 14, 45 122
 Great Britain, 4, 7-8
 Green manures, 140-141
- Half life, 32, 60 63 65 99 184
 defined, 205
 elements useful in biology 148
 plant food elements, 136
 Half thickness, 206
 Hamilton, 161-162
 Hanford, Wash. 12 76, 83 86
 Hard gamma emitter 94-99
 Hauser, E. A., 130 n.

- Health hazards, chain reaction by products, 52-53
 pile, 45
 power plants, 16-17 49-51 81
 radioactivity 90-91 93 110 162-163 165 168 183-185
 Heat, production of 12-14
 Heat exchange mediums, 81-83
 Heat exchangers, 13-14 78 117-118
 Heavy water 14, 153 155-156 157
 defined, 206
 Helium, 34, 37-38 39, 40, 77 83
 defined, 206
 Helium ions, 39
 Hemoglobin formation, 150
 Hertz, 160-161
 Hershey George von, 152-153, 156-157
 Hiroshima, 2, 6, 16, 46
 Hold up, 206
 Homocystine, 154
 Hormones, 178
 see, 171
 Hydrogen, 30, 32 ff., 39 77 107
 116-117 147-148
 heavy see Deuterium
 Hydrogen ions, 33 39
 Hydrogen sulfide, 93
 Hydroponics, 180
 Hydroxyl, 148
 Hyperthyroidism 159-163 170
 Illinois Agricultural Experiment Station, 133
 Industry atomic energy in, 47-51
 chain reaction products in, 51-57
 radioactivity in, see Radioactivity
 See also Reactors
 Initial ionizing event, 206
 Integrating circuit, 206
 Iodine, 151 160-161 163-164
 radioactive, 147-148, 151 159-166
 Ion, 206
 Ionizing rays, 16-17
 See also Radiation
 Ionization, 59, 63-64, 68
 defined, 206-207
 Ionization chamber 61 67 70-72
 defined, 207
 Ionizing event, 207
 Iowa State College, 125-1 6 130
 Iron, 80 10
 diffusion research, 106-107
 radioactive, 106-107 136 150-151
 Isobars, 207
 Isotopes, 36, 38 41 43 44, 126
 defined, 07
 radioactive, see Radioisotopes
 separation methods, 07-208
 Isotron 08
 Jet engines, see Aircraft
 Joule, 209
 k factor see Multiplication factor k
 Kaolinite (clay) 125 127 128
 Kirkendall effect, 107
 Knipping, 183
 Lamellas, 109
 Lattice, 209
 Lattice vacancies, 107
 Laue, Max von, 183
 Lawrence, E. O. 40
 Lawrence, John, 166
 Lead, 32, 121
 Lead sulfate, 179
 Lester Dr 164
 Leucine, 156
 Leukemia 42, 160 166-170
 See also Cancer
 Leveling method, radioactive, 71
 Light sources, radioactive, 6, -66
 Lime, 13, 144
 Linear accelerator 09
 Linear amplifier 09
 Linoleic acid, 155
 Linolenic acid, 155
 Liquid level gage, radioactive, 96-97
 Lithium, 34-36, 40 77
 Los Alamos, New Mex 6 52
 Lubricant technique, 1-9 130
 Lymph glands, 166 167
 Lymphatic leukemia, 169-170
 Lysine, 155

- Magnesium, 41
 oxide of 126
 radioactive, 136
 Magnetron, 209
 Manganese, radioactive, 136
 Manhattan Project, 90 184
 ceramic work, 124-128 130
 Metallurgical Laboratory 124-128
 Mannure, green, 140-141
 Marine propulsion, atomic, 50 86
 Marmelli, 163, 164-165
 Mass, 36-37 209
 critical, 74-75
 defined, 198
 Mass energy equivalence, 209
 Mass number *see* Number
 Mass spectrometer 44
 defined, 210
 Massachusetts Institute of Technol-
 ogy 126
 Medicaments, 177
 Medicinal plants, 181
 Medicine, radioactive tracers in, 159-
 172
 future uses, 170-172, 182-185
 leukemia 160 166-170
 polycythemia, 170
 thyroid cancer 162-166
 thyroid overfunctioning, 159-162
 safety limits, 162-163
 Mehl, R. F., 105 n.
 Menlo Park, N. J. 19
 Mercaptans, 93
 Mesons, 52
 defined, 210
 Metabolism 146-147 152-153, 154-
 158
 Metallurgical Laboratory Manhattan
 Project, 124-128
 Metallurgical research, radioactivity in,
 101-111
 liquid metals, 101-105
 solid metals, 105-110
 Metastases, 164
 Methionine, 153-154
 Mew 210
 Micro 210
 Micrometer radioactive, 71-72
 Military Commission 8-11
 Milli, 210
 Millikan, Robert A. 29-30
 Moderators, 14, 77
 defined 210
 Molecule, 211
 Monsanto Chemical Co. 52
 Montefiore Hospital, 164
 Moseley Henry 33-34
 Multiplication factor k , 124-126
 defined, 211
 Mustard gas, 154
 Myelogenous leukemia, 167-168, 170

 Nagasaki, 2, 6
 Neptunium, 43 53
 defined, 211
 Neubauer test, 140
 Neutrino 54
 Neutrons, 12-13, 14, 34-45 51 66,
 74-77 78 79-81 120-122, 124-
 125 173
 defined 211-212
 slow 220
 Nickel, 107
 Nitrides, 126-128
 Nitrogen 33 39 56 107
 radioactive, 136, 147-148 152,
 154 156 157
 Non self quenching counter tube, 212
 Nuclear Energy for the Propulsion of
 Aircraft Project, 112 n.
 Nuclear fission, *see* Fission
 Nuclear physics, 38
 Nucleus, 32-34, 37 43 74-75
 defined, 212-213
 Number atomic, 34-36, 38 defined,
 194-195
 mass, 34 38 defined, 210

 Oak Ridge, Tenn., 12 76, 82 83 135
 207
 Office of Naval Research, 101
 Ohm, 213
 Operating voltage, 213
 Opium, radioactive, 56
 Oppenheimer J. R., 9
 Overshooting, 213

- Overvoltage, 213
 Oxidation, 108-109
 Oxides, 126, 129
 Oxygen, 36, 39 117
 isotopes, 38, 56 147-149
- Paper industry 92
 Parathyroid gland, 150
 Pearlite, 105, 109
 Periodic table, 213-214
 Permeability 150, 153
 Perrin, F 63 n 64 n
 Petroleum refining, 92
 Pharmaceutical research radioactive
 tracers in, 173-181
 as therapeutic agents, 175-176
 as tracer elements, 177-178
 in pharmaceutical chemistry 179-
 180
 in pharmacognosy 180-181
 in pharmacology 178-180
 in pure pharmacy research, 177-178
 Philadelphia, Pa 6
 Phosphate Research Committee, 137
 Phosphates, 138 140, 141 156-157
 efficiency of 142-143
 radioactive, 135
 Phospholipids, 156
 Phosphorus, 134-143 157
 radioactive, 42 134-143 156, 160,
 166-170
 Phosphorus metabolism, 156-157
 Physicists and radioactivity 54
 Pike, see Reactors
 Plant food elements, radioactive, 135-
 137
 Plant growth, radioactivity and, 133-
 134
 Plants, medicinal, 181
 Plaster technique, 129-130
 Plastics industry 92
 Plateau, 215
 length of 209
 Plateau slope, normalized, 212
 relative, 219
 Plutonium, 12 ff 19, 43, 45-46, 53
 54-55, 75-76, 82
 defined, 215
- Police, international, 3-4
 Polonium, 3-, 51 60 63 68
 defined, 215
 Positron 36
 defined, 216
 Potassium radioactive, 136, 153
 Potatoes, 137 141 143
 Power 16
 Power plants, atomic, 12-18
 design, see Reactors
 economic aspects, 15-16 17-18
 49 85-88
 for aircraft see Aircraft
 health hazards, 16-17 49-51 81
- Predissociation 16
 Promethium 53
 Proportional counter 216-217
 Proportional region, 17
 Prostate gland, cancer of 171
 Protein metabolism, 156
 Protoactinium 17
 Protons, 33-42
 defined, 217
 Protoplasm, 153
- Quantum, 17
 Quenching, 217
 Quenching circuit, 217
 Quenching vapor 217
- Radar 1-9
 Radiation 16-17 45 50 64 110
 119 120-122 162-163 183-185
 defined, 217
 Radiation sickness, 175
 Radioactive equilibrium 217-18
 Radioactivity 13 30-31 41-42, 80-
 81 83-84
 defined, 218-219
 health hazards, see Health hazards
 industrial applications, 58-7-, de-
 tecting displacement, 69-72,
 using ionization power 59-66
 using penetrating properties, 67-
 69
 tracer applications, see Radionu-
 clides

- Radioautograph technique, 147-179,
180-181
- Radionuclides (tracers) 54-57 58 62,
89-90
defined, 221
uses, *see* Biology; Chemical process
control; Medicine; Metallurgical
research; Pharmaceutical research;
Soil-fertilizer research
- Radium, 17 31 32, 37 39, 41 54,
58-59, 60, 67 152, 160
defined, 219
- Radium water 184
- Radon, 32, 60
defined, 219
- Ram jet, 115-116, 1-9
- Rate meter *see* Integrating circuit
- Rayon industry *see* Chemical process
control
- Reactions, tracing, 98-99
- Reactors, 1 n 45, 50, 51, 53, 125,
173-174
defined, 214-215
design problems, 77-85
fast, 76-77 79
for aircraft, *see* Aircraft
nuclear engineering, 73-77
shields, *see* Shields
thermal, 76-77 79-80
See also Power plants
- Reading, Pa., 6
- Recovery time, 219
- Refractory containers, 124-128
- Region of limited proportionality 219
- Relative plateau slope, 219
- Reproduction factor *see* Multiplica-
tion factor *k*
- Resistors, radioactive, 61-63
- Resolving time, 219
- Resonance energy 219
- Rockets, 3, 6
atomic engine, 116-117 129
- Roentgen, Wilhelm Karl, 29, 182
- Roentgen defined, 219
- Roentgen rays, *see* X rays
- Rubber industry 92
- Russell, Sir John, 133
- Russell, Ralston, Jr., 129
- Russia, 4, 7 22
- Rutherford, Ernest, 31-33, 38-39
- Rutherford defined, 219
- Rye grass, 140
- Scaling, 108-109
- Scaling circuit, 220
- Scanning device, radioactive, 67-68
- Schoenheimer, 154, 157
- Schreiber Alan P., 89-100
- Science, and atomic energy 46-47
and products of chain reaction,
51-57
- Seidlin, Dr., 164
- Self-absorption, 220
- Self-quenching counter tube, 220
- Separation factor, *see* Enrichment
factor
- Serme, 154
- Service and technology 21-23
- Sex hormones, radioactive, 171
- Shields, aircraft, 118-122
reactor 14, 50, 81
- Ships and atomic energy 50, 86
- Silica, 103
- Silicon, 107
- Silver-copper system, 108
- Silver-zinc system, 109
- Slag metal interface reaction, 101-102,
104, 107
- Slags, 103-104
- Slow neutrons, 220
- Smyth, H. D., 14 76 n, 124 n
- Sodium, radioactive, 40-41 136, 153
- Sodium sulfate, 98
- Sodium sulfite, 98
- Soil fertility 138-140
- Soil fertilizer research, radioactive,
132-144
influence of radioactivity on plant
growth, 133-134
radioactive tracer technique, 134-
137
radionuclides of plant food elements,
136
results of experiments, 137-144
- Soley 161

- Spark plugs, alumina, 129
- Specific gravity measurement with radioactivity 94-96
- Spectrometer *see* Mass spectrometer
- Spurious counts, 220
- Starting potential, 220
- Starting voltage, 0
- Static electricity determination of 64
- Static eliminators, radioactive, 59-61
- Statistical time lag, 2 0
- Steelmaking, *see* Metallurgical research
- Sulfides, 1 6-128
- Sulfite paper pulp, 92
- Sulfur 9 -93 96 10 136-137
 - radioactive, 92-93 98 102-103
 - 136, 151-15-, 153-154
- Sulfur transfer coefficients, 102
- Superphosphate, 136-137 140 142
 - radioactive, 135
- Supersonic aircraft, 112, 113
- Supph voltage, 220
- Table, periodic, 213-214
- Tablets, 177
- Technetium, 53
- Technology effects on society 18-25
- Tennessee Eastman Corp 52
- Ternary alloys, diffusion in 106 108
- Thales, 28
- Therapy radioactive isotopes m, 175-176
- Thermal diffusion, 220
- Thermal reactors, 76-77
- Thermal utilization factor 220
- Thomson, J J 28-29 30, 32
- Thorium, 15 ff., 79 83-84, 85
 - defined, 220-221
 - oxide of, 126
 - sulfide of 126
- Thyroid gland, 151
 - cancer of, 16 -166, 170
 - overfunctioning, 159-162, 170
- Thyroxine, 160-161 164
- Tobacco 13,-138 141-142
- Tonnage meter radioactive, 70
- Toxicity 1,9
- Tracers, *see* Radioisotopes
- Training, need of 20-21
- Transmutation, 12-13 24
 - defined, 221
- Transuranic elements, 53 221
- Tritium, 221
- Turbo-jet, 114-115 129
- Union Carbide and Carbon Corp 52
- United Nations Security Council, 8 ff
- United States government, 4 7-8
- Uranium 12 14 ff., 31 32, 36 42-45
 - 49 51 54-55 75-76 79 63 8,
 - 117 118 120, 125-1 6 194
 - defined, - 1- 3
 - U²³² 75 76 79
 - U²³³ 14 44-46 74-76 79
 - U²³⁸ 44-45 74 75-76 77
- Uterus, cancer of 171
- Vacuum tubes, 66
- Van de Graaf generator 39
- Vapor quenching, 217
- Vapor pressure measurements, 104-105 109
- Viscose, 92
- Vitamin D 150
- Vitamins, 178
- Volt, 2 3
 - See also* Electron volts
- Voltage, operating, 13
 - starting, 0
 - supply 2 0
- Voltage pulse, 23
- Voltmeter radioactive electrostatic, 63-64
- War prevention of 2-11
- Water as coolant, 82
 - heavy *see* Heavy water
 - radium 184
- Wavelength, 3
- Weight, atomic, 34-36 77
 - defined, 195
- Wheat, 140
- Whipple George Hoyt, 150
- Wilmington, Del 6

Work, 223

World government, 2-3, 24

X rays, 12, 17 29 33-34 54, 80 81

121 168, 169 182-183

defined, 223

Yield, 223

Zinc, 109

radioactive, 136

Zinc sulfide, 65

